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Targets for Heavy Ion Fusion Energy

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1.Lawrence Livermore National Laboratory, 2.Lawrence Berkeley National Laboratory, 3.Princeton Plasma Physics Laboratory

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Washington, DC
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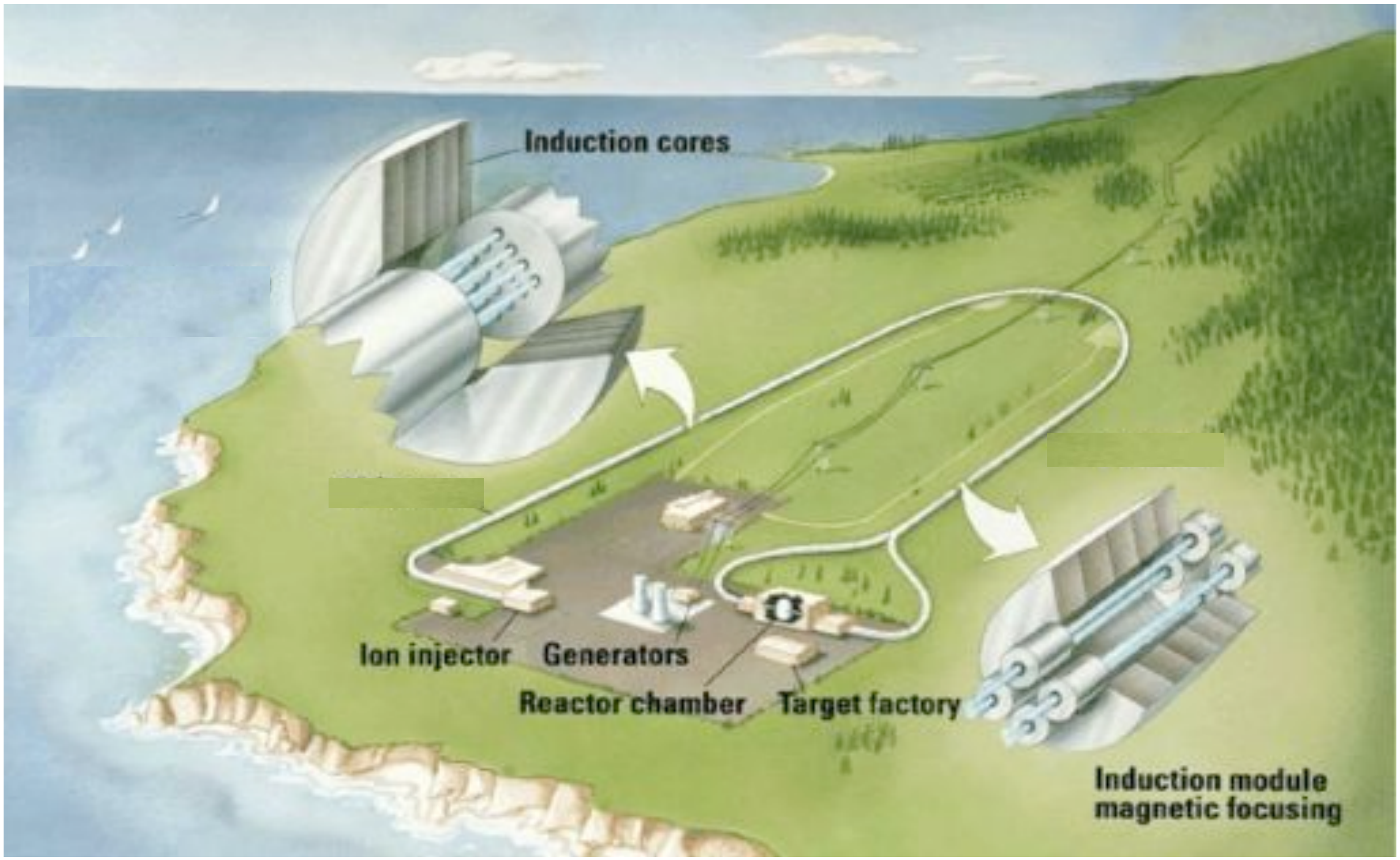
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551

Heavy ion fusion: Induction accelerator drivers are durable, efficient, and enable high pulse rates (like transformers)



Heavy ion accelerators of multi-MJ fusion scale would be comparable in scale to today's large NP accelerators like GSI-FAIR, RHIC $\Rightarrow$ Economical for 1-2 GW_e baseload power plants.

Why heavy-ion drivers for inertial fusion energy?

- **Established accelerator base:** High energy particle accelerators of MJ-scale beam kinetic energy have (separately) exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE (→transformers)
- **Robust final optics and chamber transport:** Focusing magnets for ion beams avoid direct line-of-sight damage from target debris/n-ϒ-radiation, and could last many full-power-years.
- **Thick-liquid-protected chambers:** Offer >30-year lifetime, no blanket changeout, potential near-surface-disposal of waste, and may avoid the need for a 14-MeV-neutron materials development program
- **Unique target dynamics:** Heavy ions stop by *dE/dx* with near-classical deposition (lasers stop at critical density and can undergo parametric instabilities). Ion range can be tailored by control of beam kinetic energy, ion species and target materials (→single-sided drive targets?)

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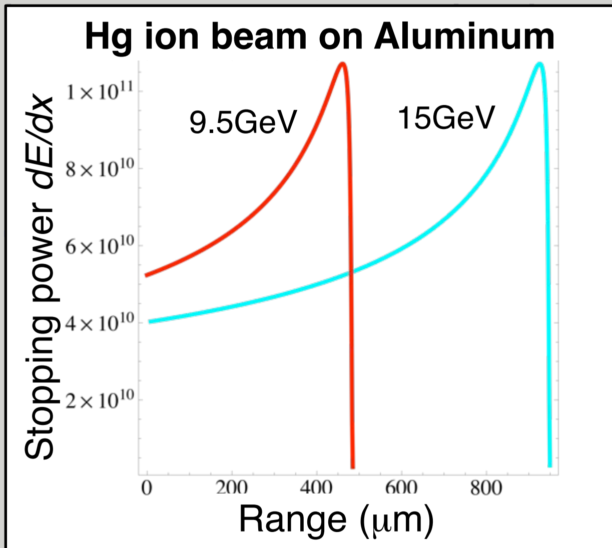

- … hamb … et
  … dispos … a
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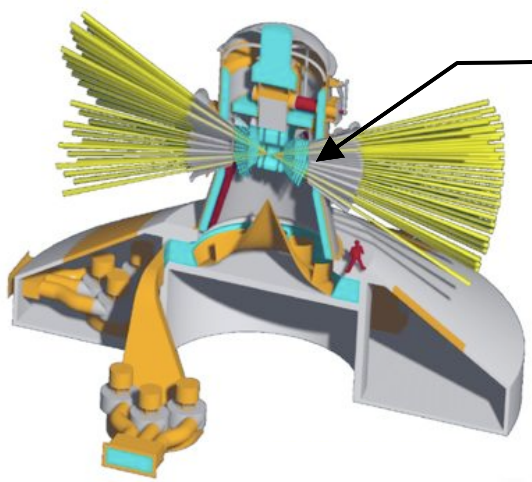
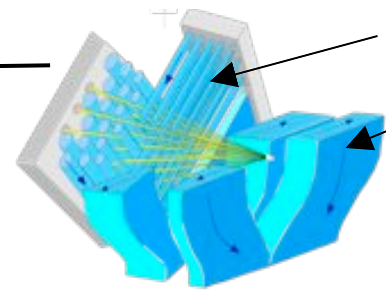
- … using … e-
  … get de … d
  could last many full-power-years

⇒ We can take advantage of the very different interaction dynamics of heavy ions relative to lasers, within the *same* radiation-hydrodynamic-burn target simulation codes

- **Unique target dynamics:** Heavy ions stop by *dE/dx* with near-classical deposition (lasers stop at critical density and can undergo parametric instabilities). Ion range can be tailored by control of beam kinetic energy, ion species and target materials (→single-sided drive)

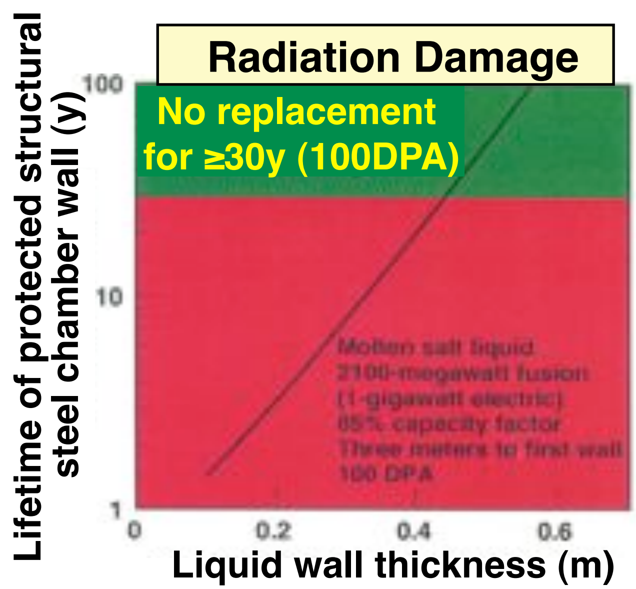
Heavy-ion power plant design: Thick liquid walls obviate 14MeV-neutron material damage and need for blanket changeout

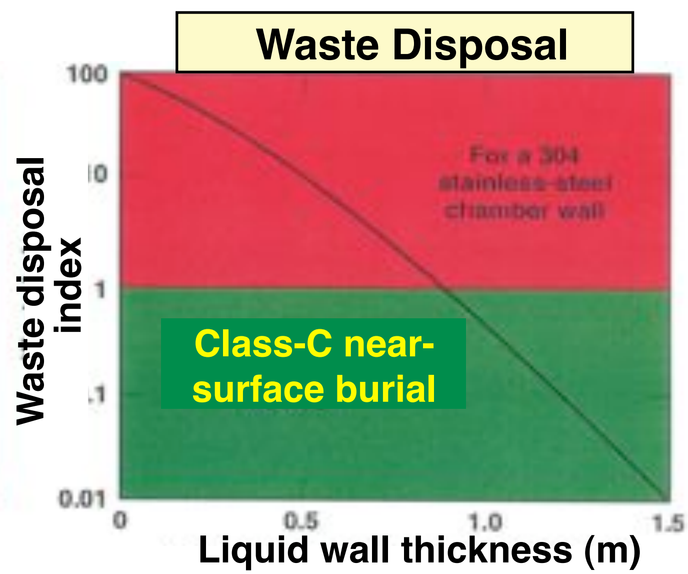




HYLIFE-II Heavy Ion Fusion Power Plant

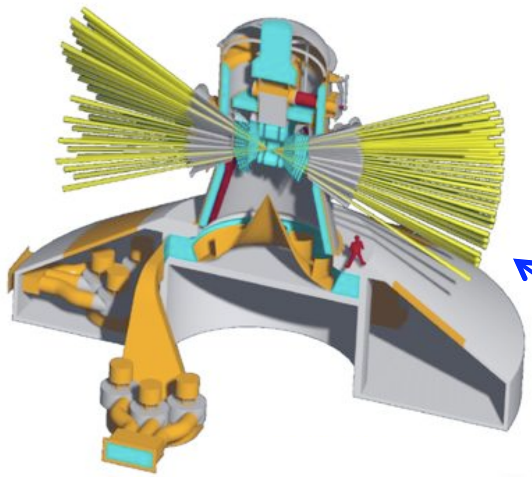
Molten salt (FLiBe) breeder-coolant forms neutronically- thick liquid wall

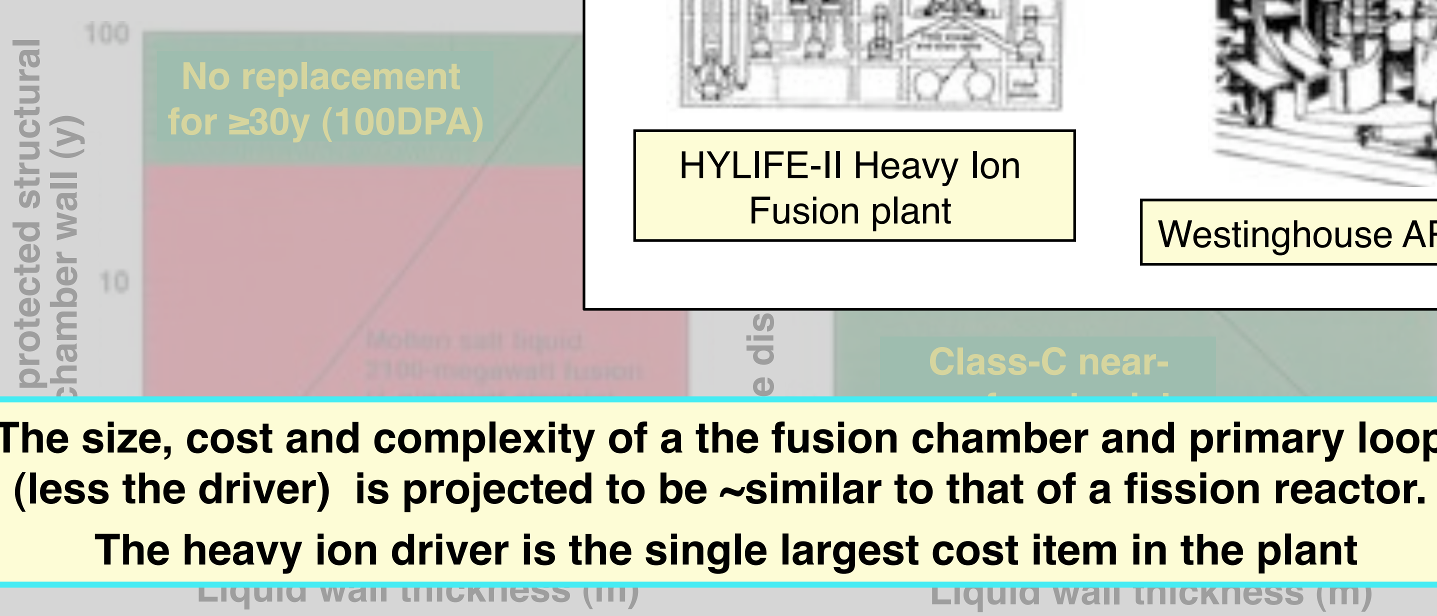


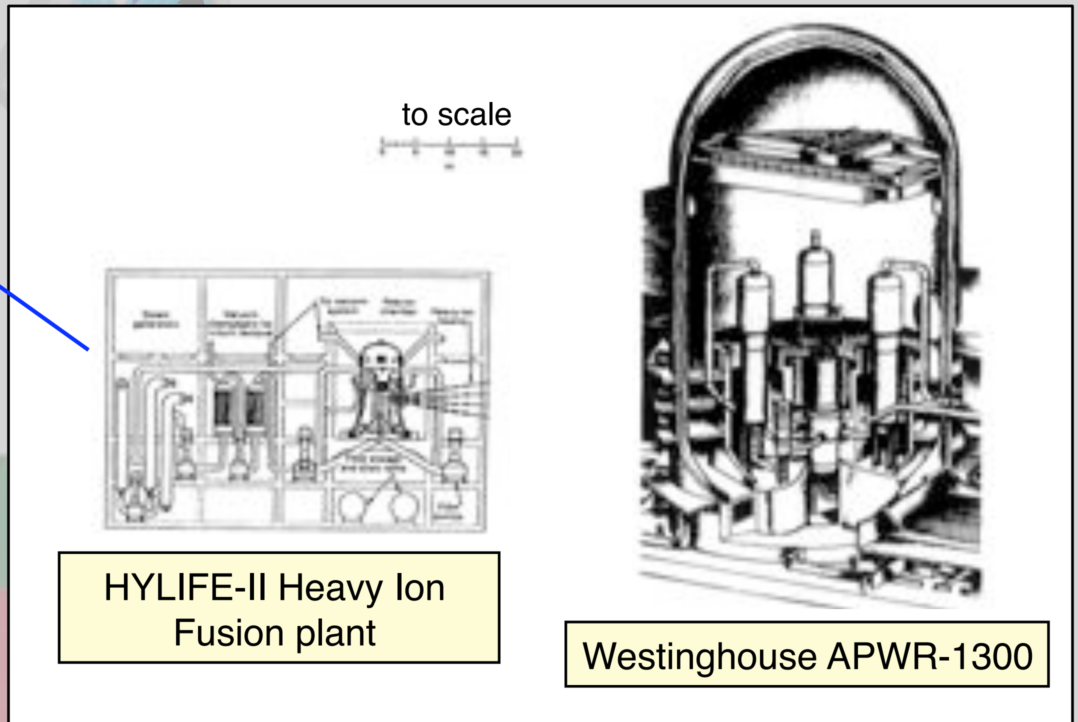


S.Sahin *Fus.Technology* 30 (1996), J.Lee *Fus.Technology* 26 (1994)

Heavy-ion power plant design: Thick liquid walls obviate 14MeV-neutron material damage and need for blanket changeout







The size, cost and complexity of a the fusion chamber and primary loop (less the driver) is projected to be ~similar to that of a fission reactor.

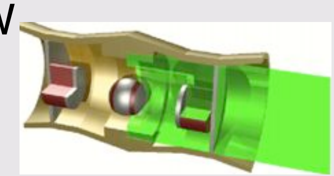
The heavy ion driver is the single largest cost item in the plant

S.Sahin *Fus.Technology*   L. J.Perkins, *Nucl. Instr. Meth. A415 (1998)*

Why *heavy* ions?

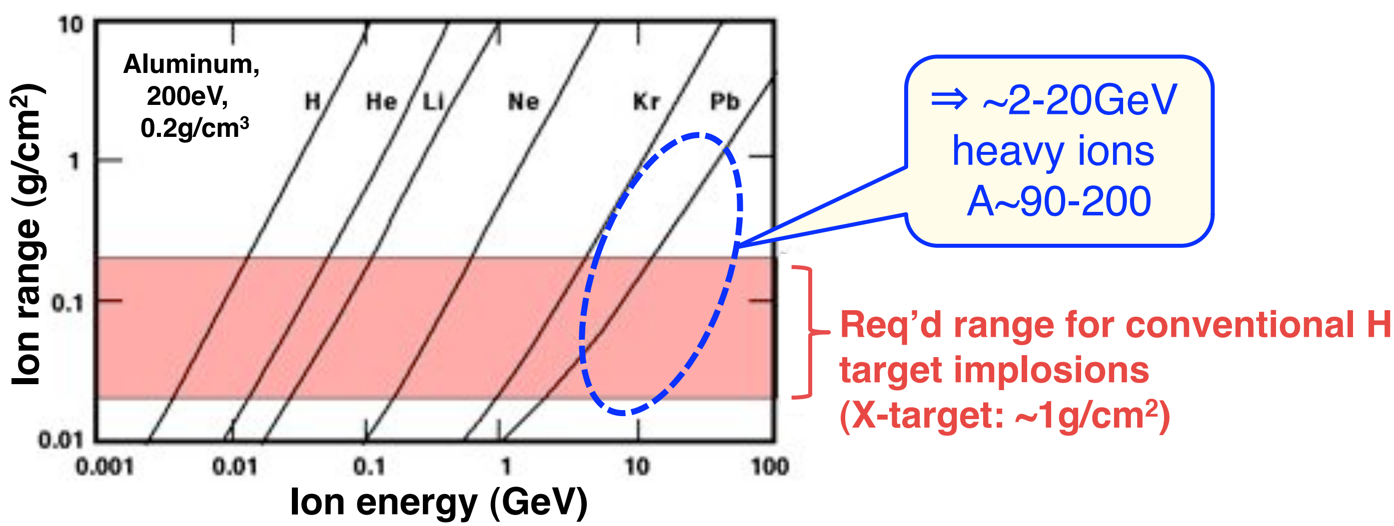
Target physics requires:

- **Energy/power:** ~2 - 6MJ drive energy delivered in ~ 10 ns, →~500TW
- **Ion deposition range:** ~ 0.02 – 0.2g/cm^2 (~1g/cm^2 for X-target)
- **Focal spot dia**: ~4-8mm



Deliver energy at higher ion kinetic energy:

⇒ lower beam current ⇒less space charge at focus
⇒ need higher ion mass to meet range stopping requirement



Heavy ion stopping in dense target plasmas is near-classical and predictable

Why *heavy* ions?

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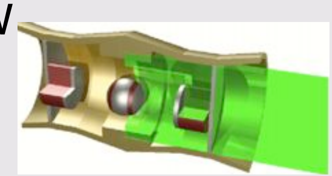
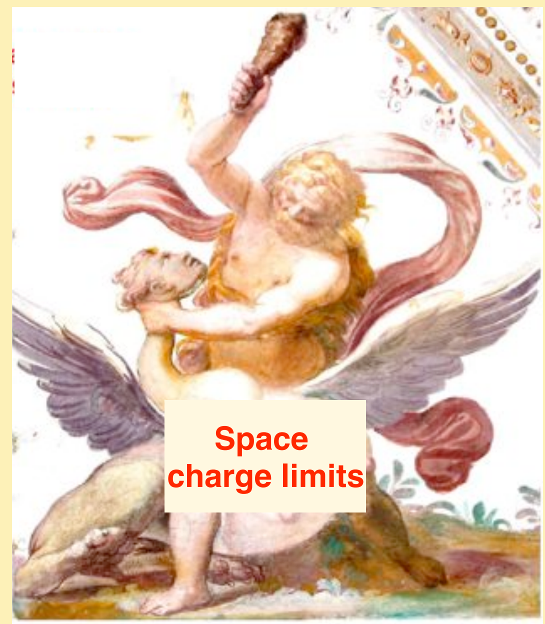


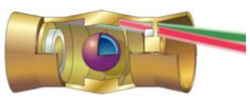
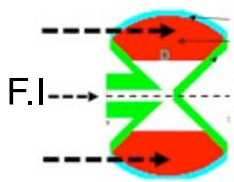
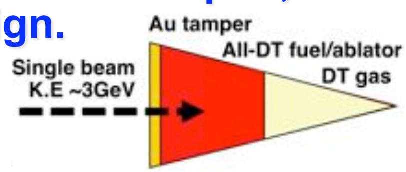
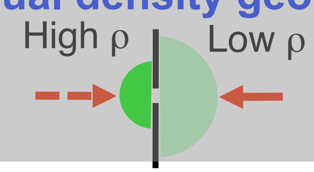
These target requirements dictate the design requirements for the heavy-ion driver:

- short pulse lengths (~10ns)
- high peak powers (~100s TW)
- small focal spots (~5mm)
- at large focal distances (~5m)

This is manageable using heavy ions at high kinetic energies



Heavy Ion Targets: There are several target classes under study....

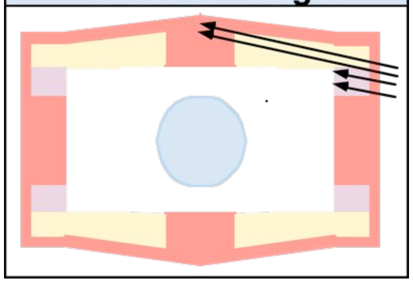
	Features	Issues
Indirect drive 	• Integrated 2D designs exist • Ablation physics on NIF • Natural two-sided geometry	• Low drive efficiency • Lower gains, high driver energies
Direct drive X-target 	• Inherent one-sided drive, all-DT • High coupling efficiencies • Reduced stability issues • Potential for high yields (~GJ) and gains	• High gains require high densities under quasi-3D compression • Higher ion kinetic energies • High power hollow beams needed for fast ignition • Driver concepts immature
Direct drive - tamped, shock ign. 	• High coupling efficiencies (tamped ablation) • Simple targets • High gains consistent with single ion-kinetic-energies (~2-10GeV)	• Optimum ion species and energy • Two-sided (polar) geometry to be established** • Stability to be confirmed
(Dual density geometry) 	• Highest potential gains • Potential one-sided drive • Application to advanced energy conversion	• Complex hydro design process to achieve two-sided assembly

An integrated target-driver R&D program can be identified for each of these target design classes.

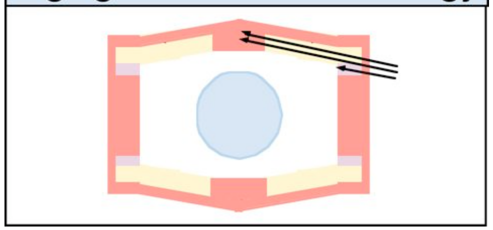
**Will leverage present NIF PDD studies

Indirect drive hohlraums with ~NIF hot-spot-ignition implosion physics: The U.S. has looked at a range of options

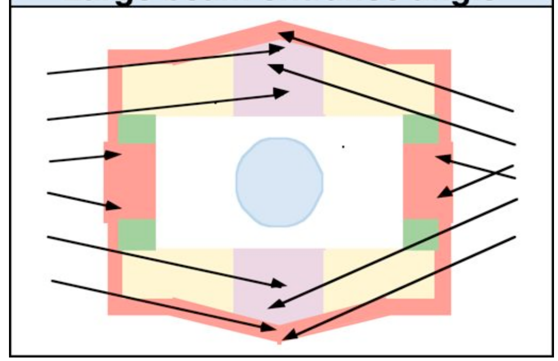
Distributed radiator: "Baseline" target



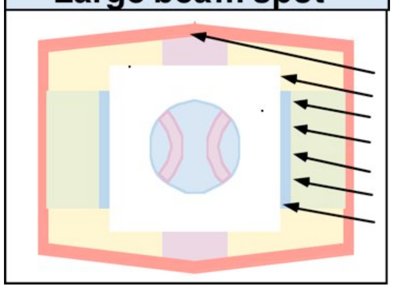
Close-coupled target: High gain at low driver energy



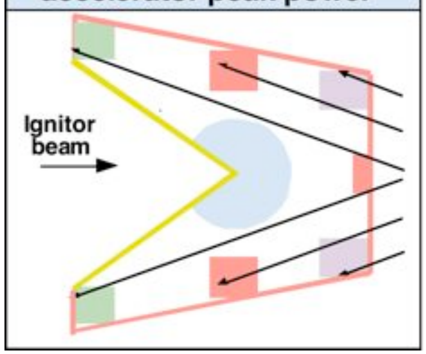
Large-angle distributed radiator: Large beam entrance angle



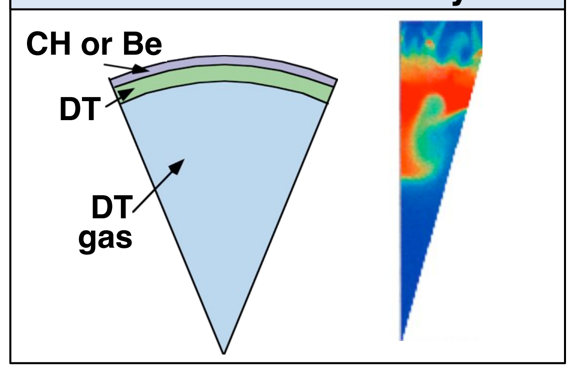
Hybrid target: Large beam spot



Fast ignitor target: High gain with low accelerator peak power



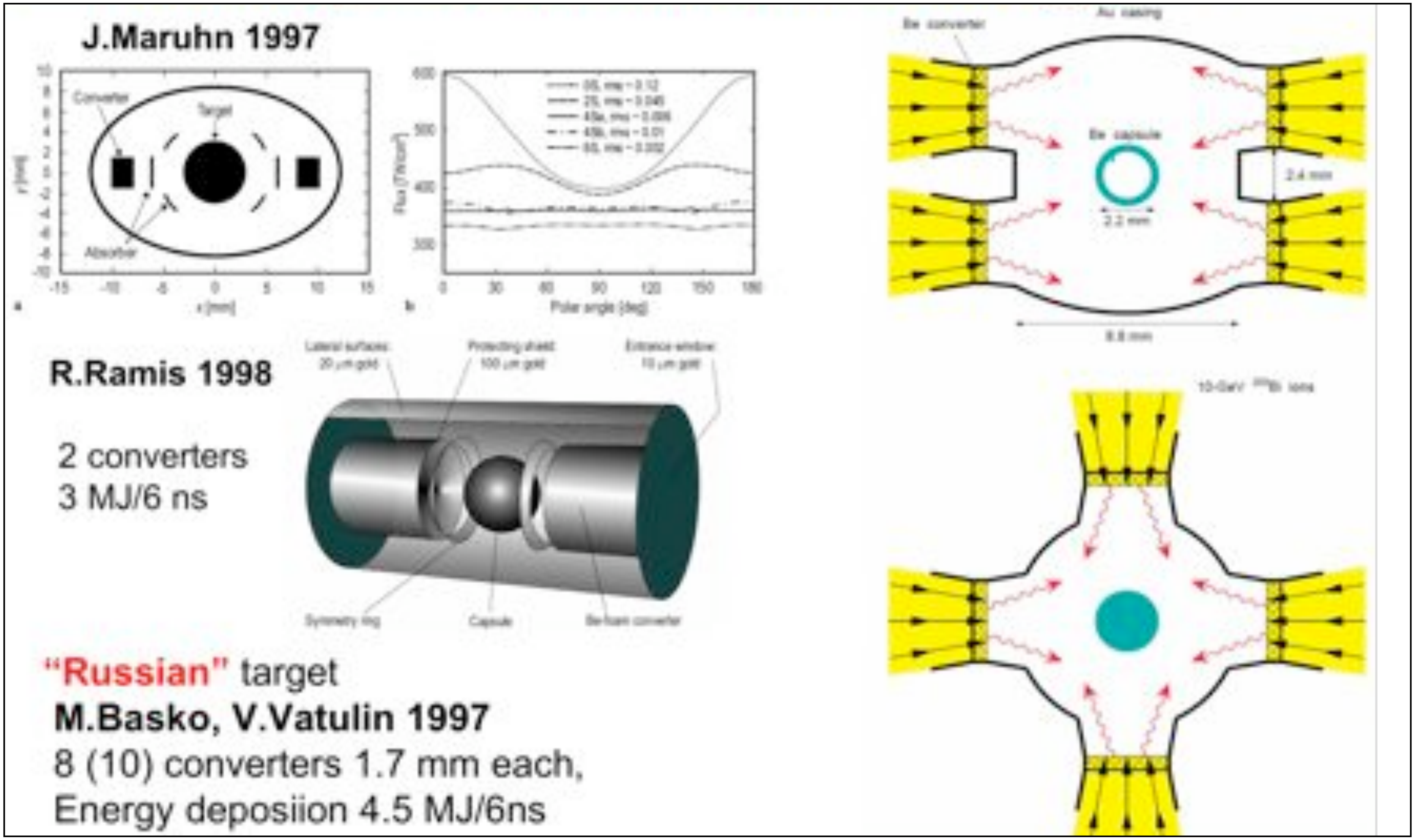
Capsule design and LASNEX 2D stability



The capsule implosion physics for indirect drive heavy ion fusion will likely be validated on NIF

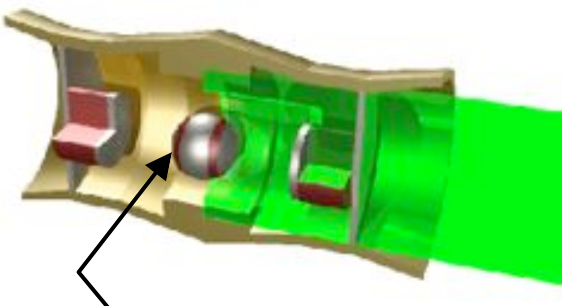
M. Tabak, *Nucl Fusion*, 38 (1998),
D.Callahan, *Inertial Fusion Science and Applications (2003)*

Indirect drive hohlraums with ~NIF hot-spot-ignition implosion physics : The Europeans have also been active in this area



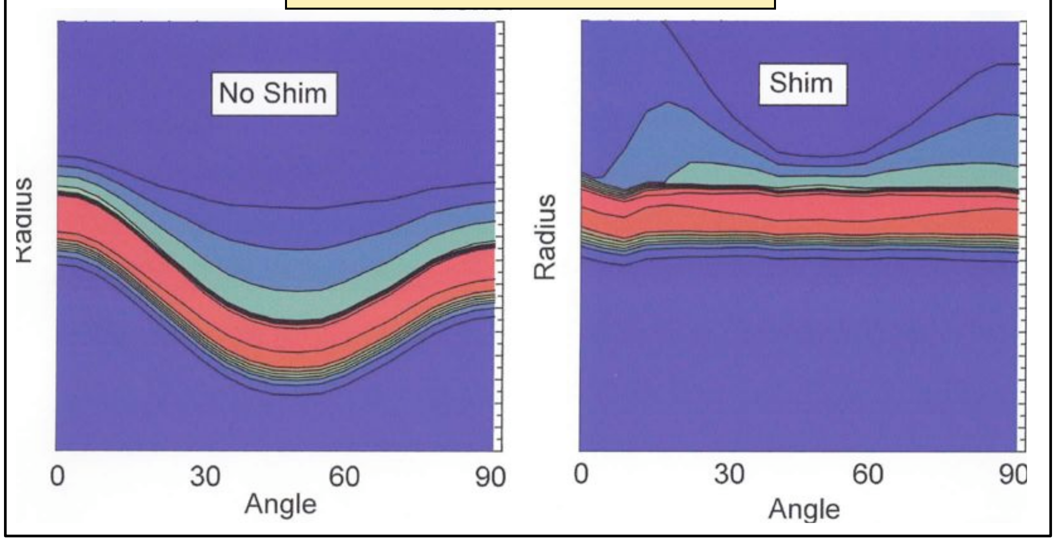
B.Sharkov *Proc. Inertial Fusion Science Applications* (2007),

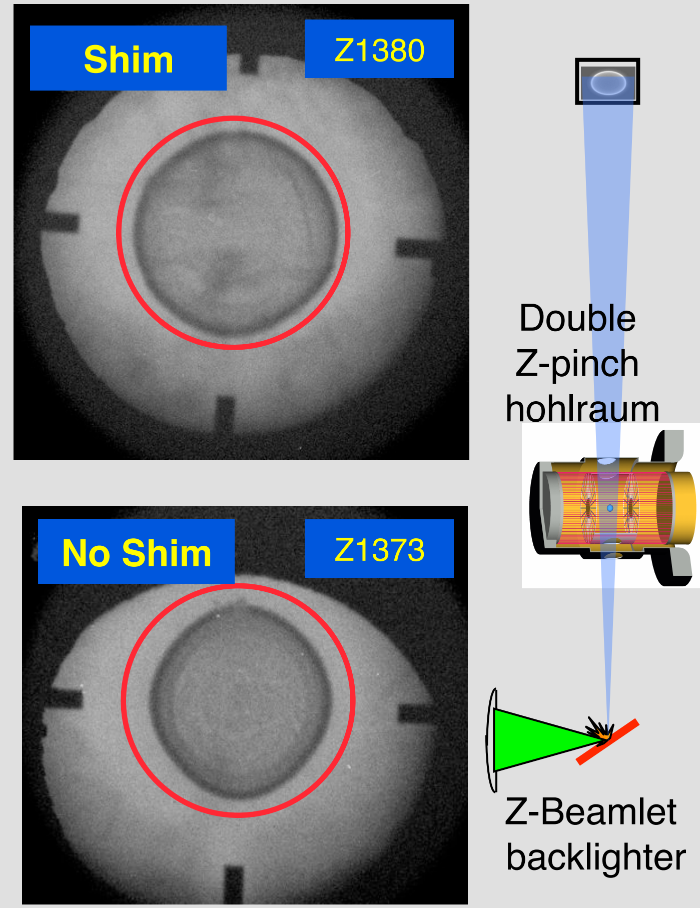
The U.S. hybrid target uses hohlraum shims for symmetric radiation flow – Shims are a relatively unexplored target optimization feature



Hybrid target:
Large beam spots
- ~8x11mm

Shims are predicted to remove P4 asymmetry on the fusion capsule

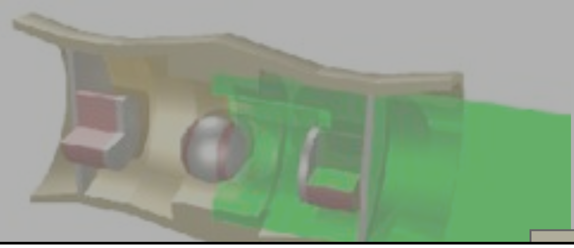


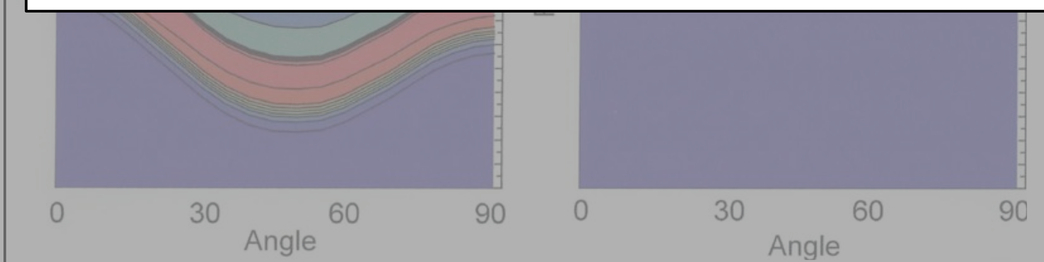


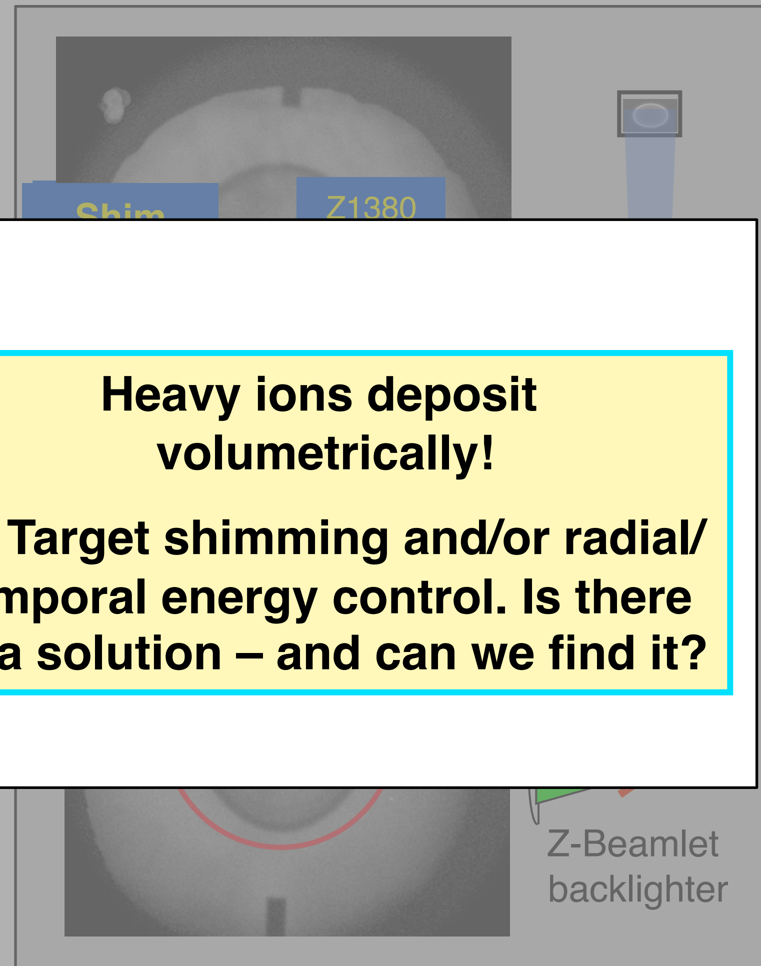
Shims have been tested in a double Z-pinch hohlraum at Sandia

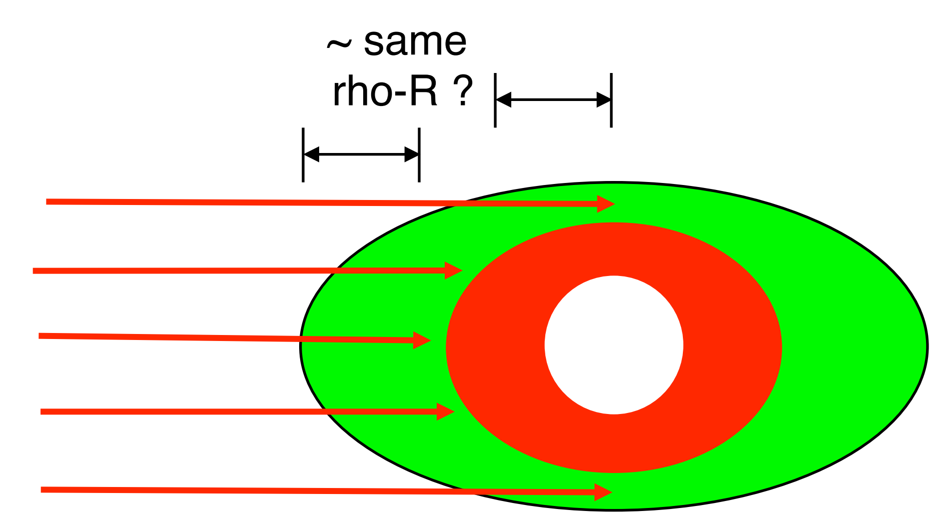
D.Callahan, *Proc 32nd Eur Conf Plasma Phys* (2005)

The U.S. hybrid target uses hohlraum shims for symmetric radiation flow – Shims are a relatively unexplored target optimization feature









Heavy ions deposit volumetrically!

⇒ Target shimming and/or radial/temporal energy control. Is there is a solution – and can we find it?

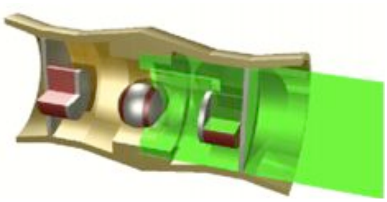
Shims have been tested in a double Z-pinch hohlraum at Sandia

D.Callahan, *Proc 32nd Eur Conf Plasma Phys* (2005)

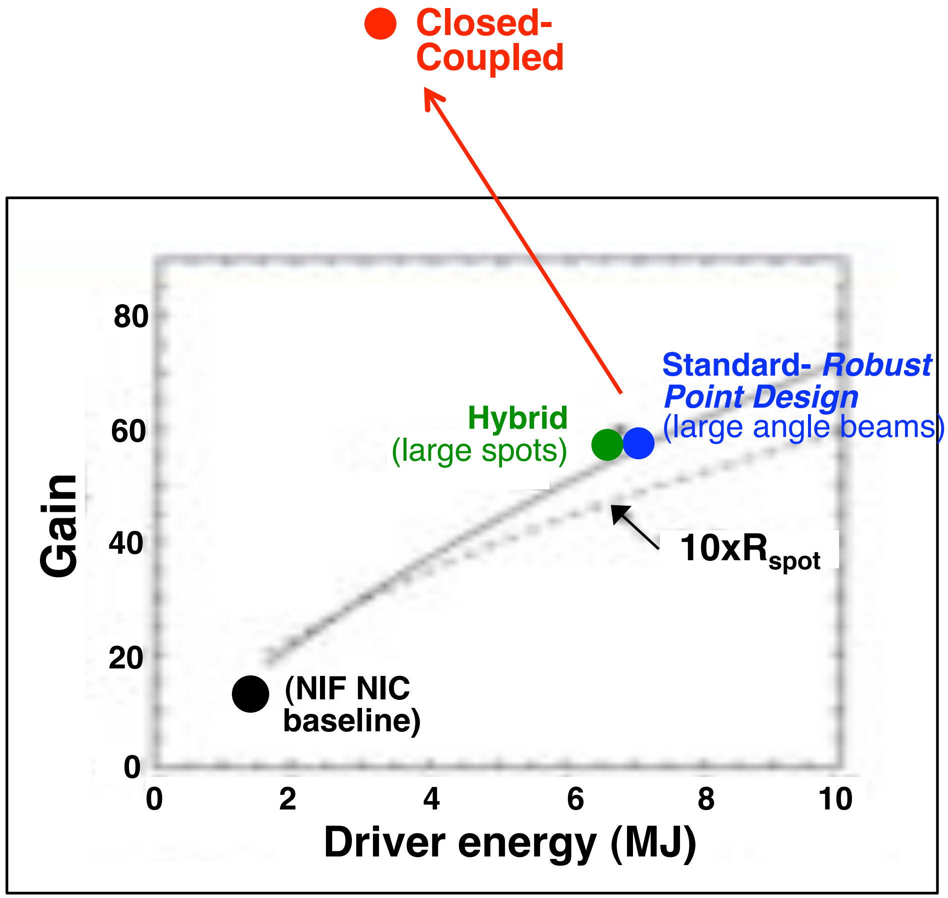
Indirect drive hohlraums with ~NIF hot-spot-ign implosion physics: Three U.S. designs have been followed in detail

Standard Hohlraum
Gain ~60 at 6-7MJ
(CCR=2.1 Beam spot ~3.5x8mm)

Close-Coupled
Gain ~130 at 3.3MJ
(CCR=1.6 Beam spot ~3mm)



Hybrid Target (shims)
Gain ~60 at 7MJ
(Beam spot ~8x11mm)



Heavy ion indirect drive will likely require larger driver energies
(but HI driver cost scales only as ~energy$^{0.5}$)

~3-4.5Gev Pb^+

17,28

D.Callahan, *Phys. Plasmas* 7 (2000), *Laser and Particle Beams*, 20 (2002).

The key to higher gain *Part-1*: Low implosion velocity

High target gain requires:

- High ρR, ⇒ more fuel burnup
- Low V , ⇒ more fuel mass assembled for given driver energy

$$G = \frac{Y_{fusion}}{E_{driver}} = \frac{Y_{fusion}}{\frac{1}{2} m_{fuel} V^2 / \eta} \sim \frac{\rho R / (\rho R + 7)}{V^{1.3}}$$

Ref. 1

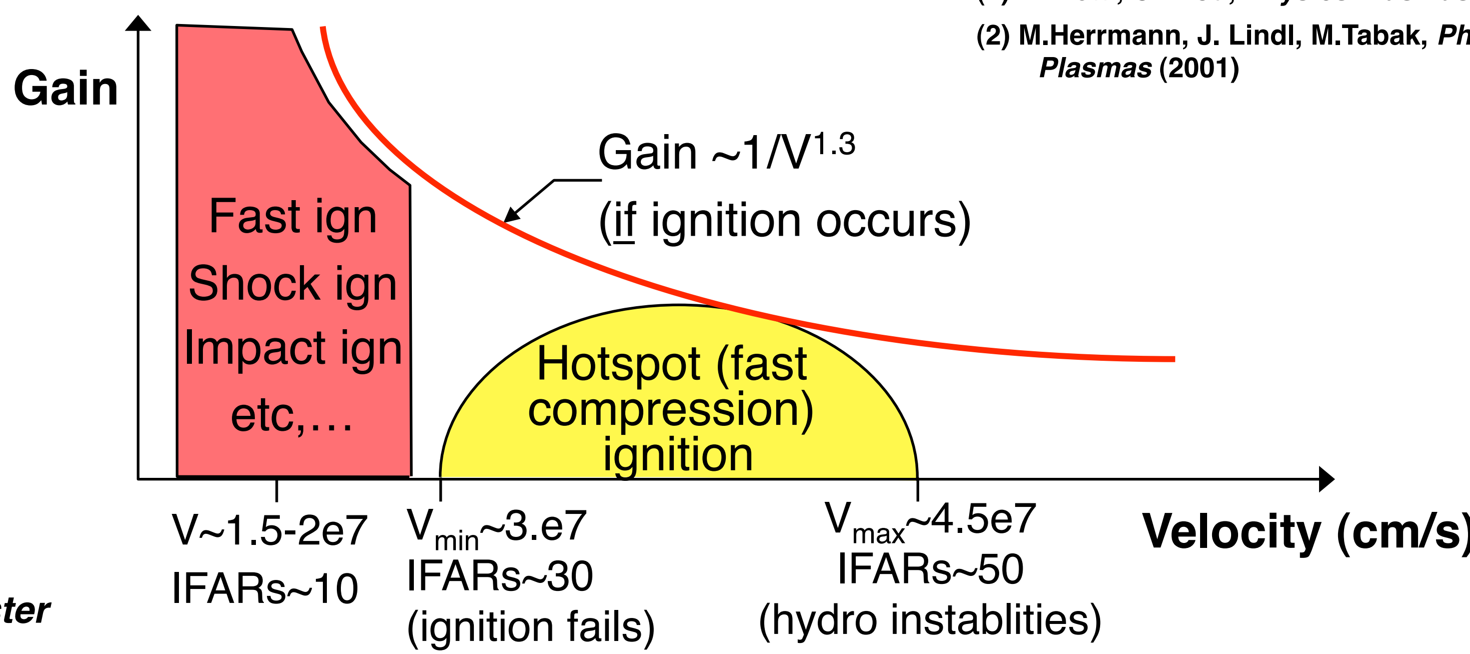
But "hotspot" (= fast-compression) ignition needs high velocity to minimize ignition energy

$$E_{ign-req'd} \sim \frac{\alpha_{FD}^{1.8}}{V^6}$$

Ref. 2

(1) R.Betti, C.Zhou, *Physics Plasmas (2005)*

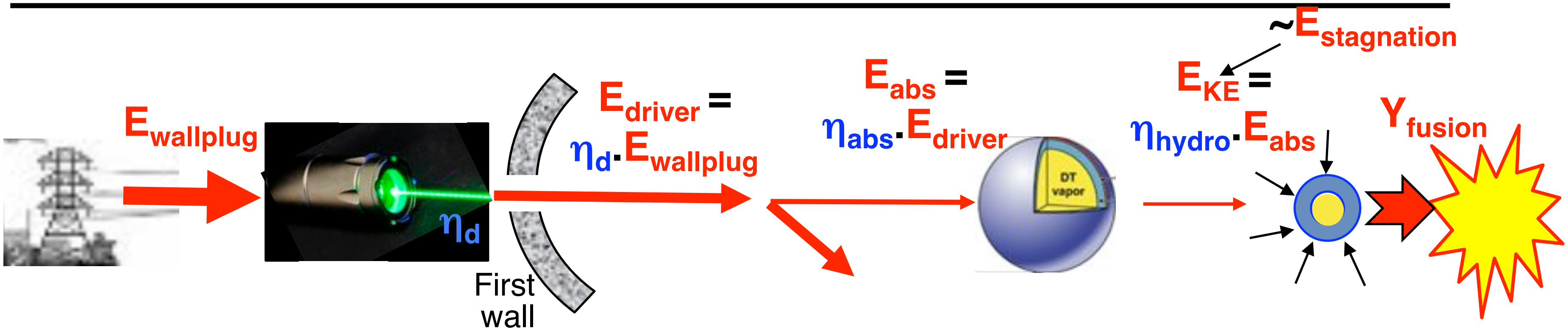
(2) M.Herrmann, J. Lindl, M.Tabak, *Physics Plasmas* (2001)

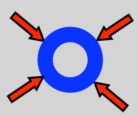
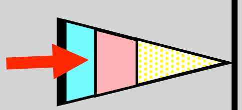
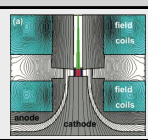


R.Betti

LLE/U.Rochester

The key to higher gain *Part-2*: High driver-target coupling efficiencies

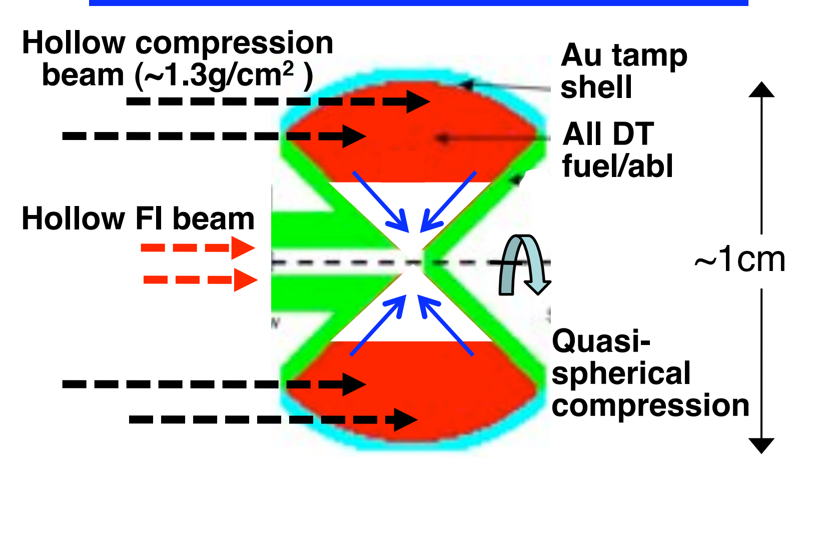


	Driver electrical efficiency η_d	Absorption efficiency η_{abs}	Hydro (rocket) efficiency η_{hydro}	System drive efficiency $E_{wallplug} \rightarrow E_{KE}$ $= \eta_d \cdot \eta_{abs} \cdot \eta_{hydro}$
Laser direct 	~0.05-0.20	~0.85	~0.06-0.1 (ablative)	~0.01
Laser indirect 	~0.05-0.20	~0.15-0.3	~0.1-0.15 (ablative)	~0.005
Heavy ion direct 	~0.25-0.40	~0.9	~0.20 (tamped ablative)	~0.05
Pulsed power direct 	~0.3	~0.2 - 0.3 (direct magnetic)		~0.05

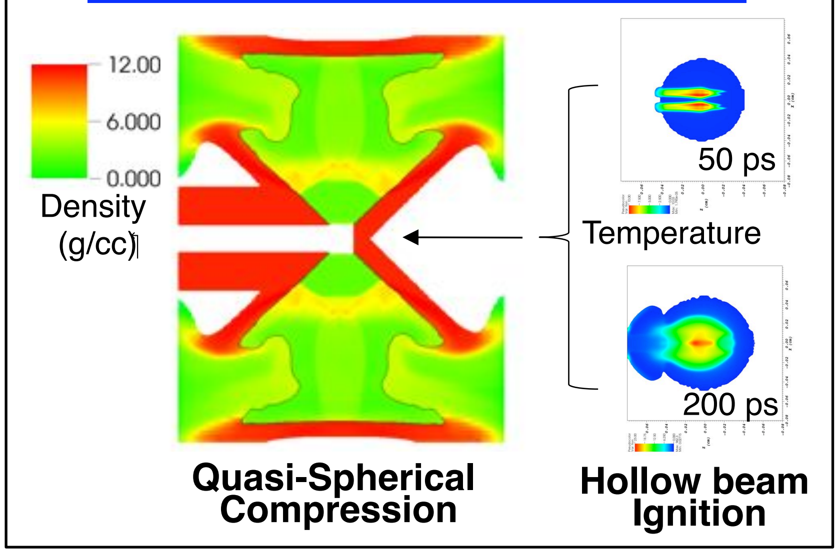
The heavy ion X-target:
Potential for one-sided drive and high gain/yield

- **Potential one-sided drive → thick liquid wall chambers**
- **Large fuel masses, all-DT, potential for high gains/yields ≥1GJ**
- **Low-velocity low-aspect-ratio fuel assembly**
- **More robust to high-mode stability – low CR~7-10 (needs fast ignition)**

X-Target



2-D Hydro Calcs



- High gain needs med-high-density quasi-spherical assembly → ***2D hydro optimization***
- Requires efficient ignition source → ***Hollow-beam fast ignition design (and B_θ lens?)***
- Effect of high-Z scrape mix in ignition region? → ***2D-3D high-mode mix studies***
- Driver design yet to be established →***Need long ion ranges ~1.3g/cm^2 (20GeV Cs…?)***

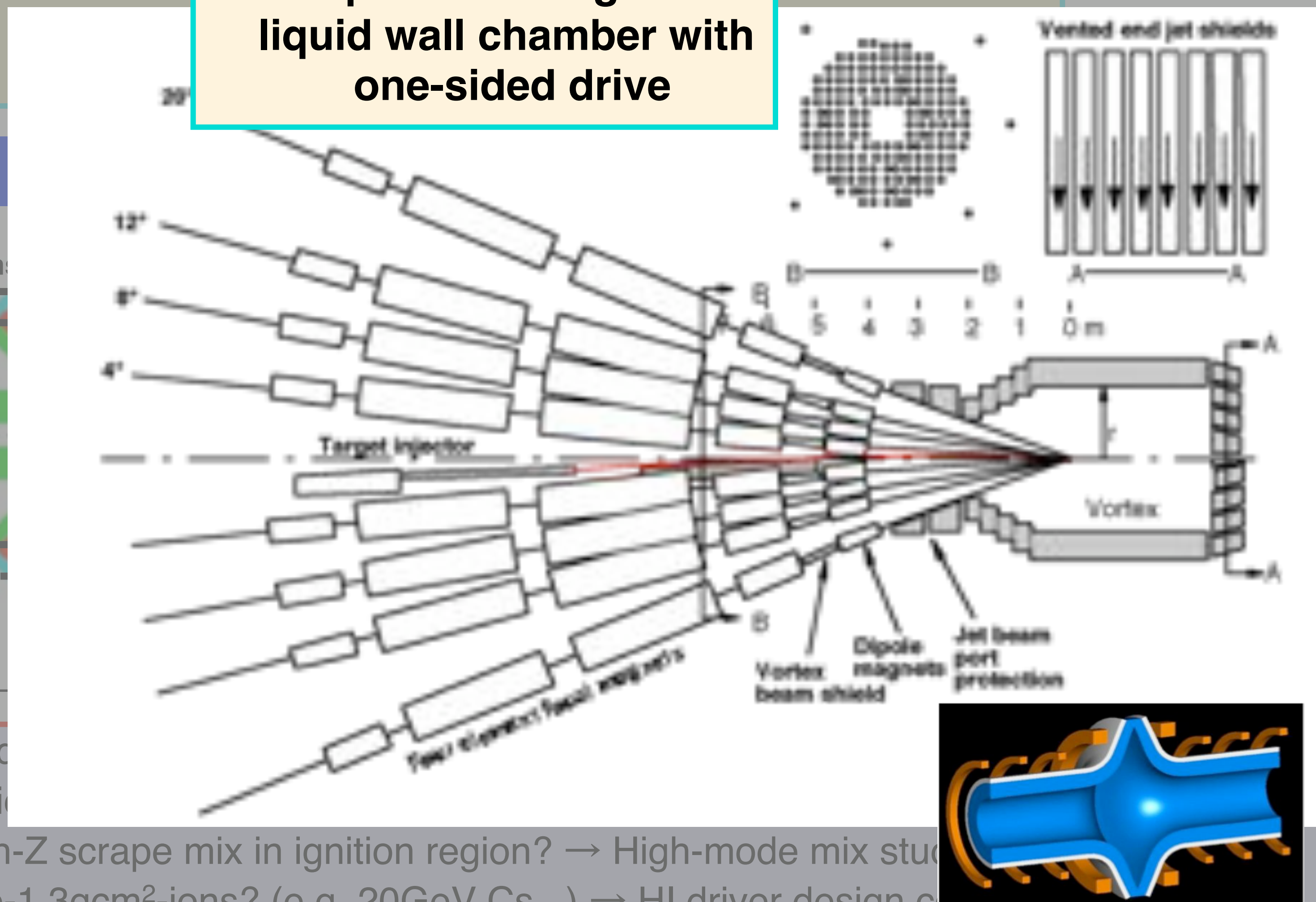
The heavy ion X-target:
Potential for one-sided drive and high gain/yield

- Potential one-sided drive (⇒thick liquid wall chambers)
- Large fue … J)

Range
~1.3g/cm² ions

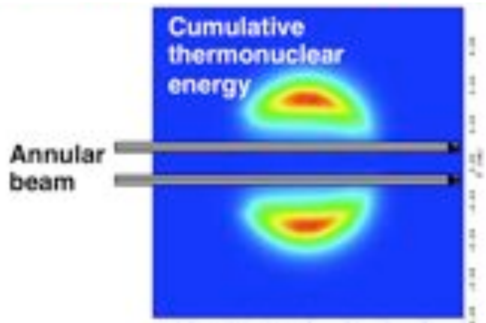
Hollow FI beam

Conceptual rotating vortex liquid wall chamber with one-sided drive

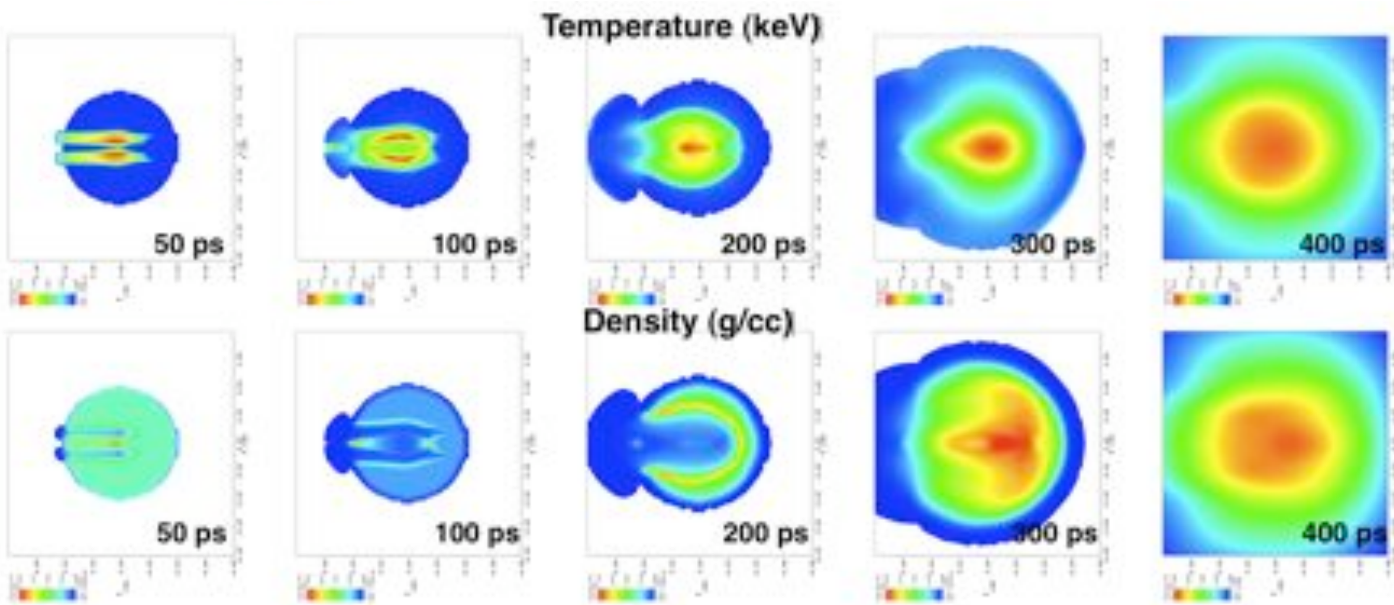


- High gain rec…
- Requires effi…
- Effect of high-Z scrape mix in ignition region? → High-mode mix stu…
- Which range-1.3gcm²-ions? (e.g. 20GeV Cs...) → HI driver design c…

The heavy ion X-target: Simulation of fuel ignition and fusion burn using a hollow heavy-ion fast ignition beam



- Previous 2D studies of hollow-beam ignition in compressed fuel have been performed by Herrmann, Tabak and Artzeni
- Here: Initial compressed fuel : 800 μm sphere, 50 g/cm^3.
- 60 GeV U hollow beam , 750 kJ, 50 ps, 200 μm dia.

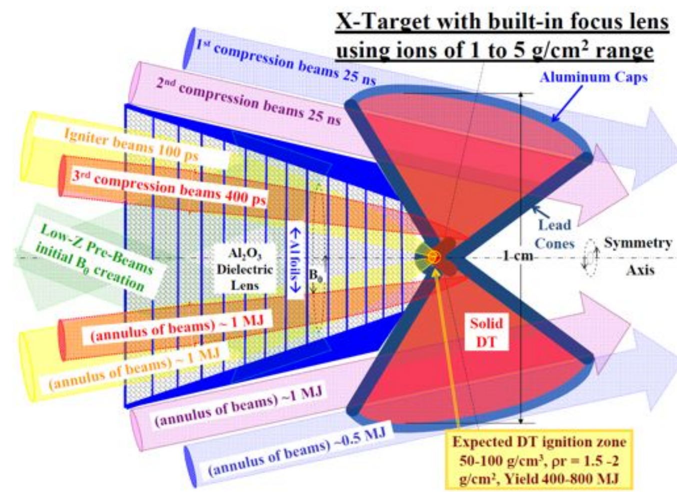


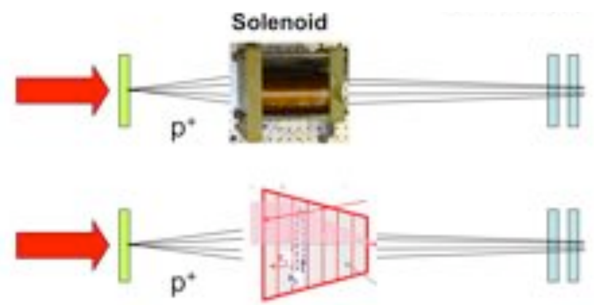
Fusion yield =750MJ

Stringent pointing, focusing and power requirements will require innovative beam physics solutions and attention to appropriate range ion species (20GeV Cs...?)

The X-target enhances 6-D phase space focusing potentially sufficient for fast ignition: But much design work to do!

Potential built-in magnetic B_θ focusing lens increases focusing angles permitting large initial spot sizes for fast ignitor beam
(~1rad focus angles over ~1cm with large ~1g/cm^2 ion range)



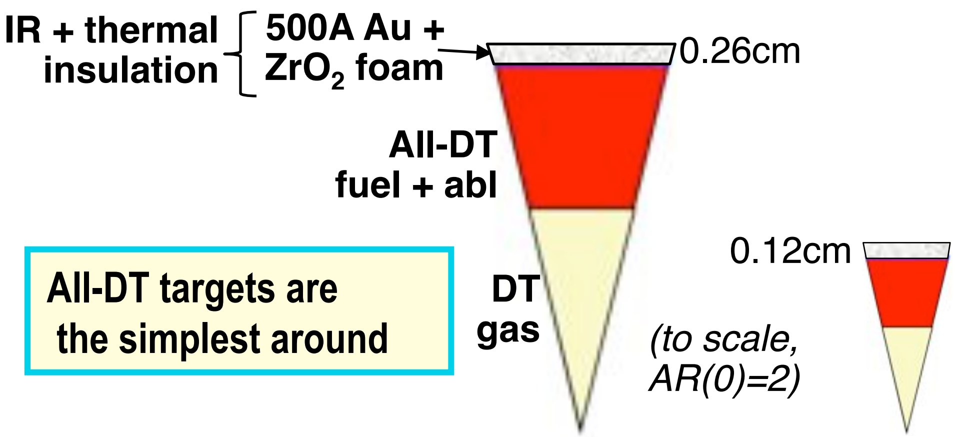


With new 100TW compressor, GSI (Darmstadt) will explore the laser driven magnetic lens in the near future

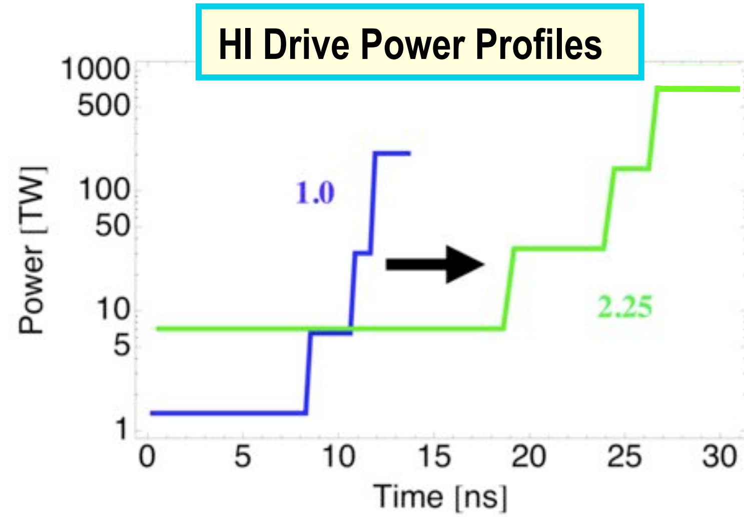
- **High gain needs med-high-density quasi-spherical assembly → *2D hydro optimization***
- **Requires efficient ignition source → *Hollow-beam fast ignition design and B_θ lens***
- **Effect of high-Z scrape mix in ignition region? → *2D-3D high-mode mix studies***
- **Which range-1.3gcm^2-ions? (e.g. 20GeV Cs...) → *HI driver design confirmation***

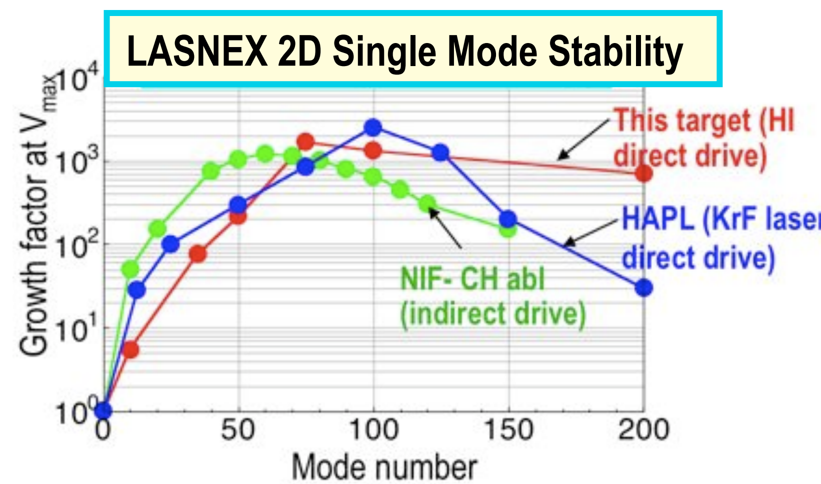
Heavy ion direct drive (untamped): Efficient drive but requires low kinetic energy beams in the foot pulse → Focusing constraints?

All-DT targets are the simplest around



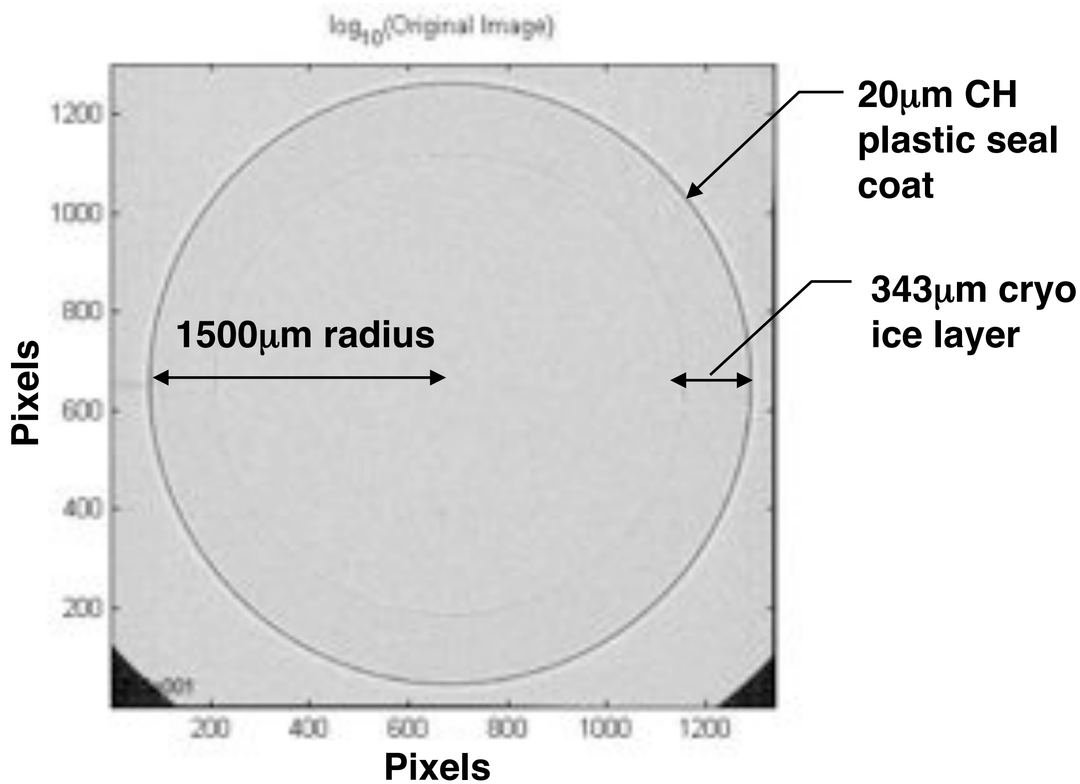
	Reactor-class	ETR-class, NIF-equiv.
Yield (MJ) / Gain	560 / 160	20.8 / 47
HI driver energy (MJ)	3.5	0.44
Ion kinetic energies foot/main (GeV)	0.22/2.2	0.05/0.5
Peak drive power (TW)	660	205
in-flight adiabat α	2.1	3.2
$\eta_{abs} * \eta_{hydro}$	0.08	0.09





B.G.Logan, *Phys. Plasmas* 15 (2008)

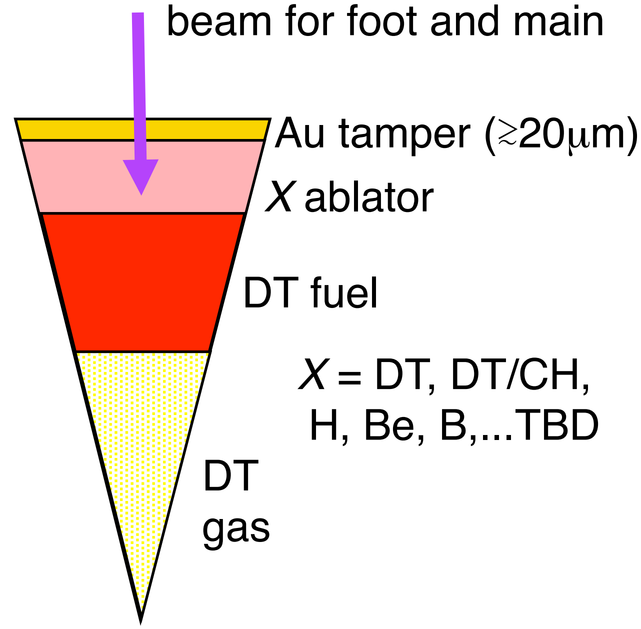
All-DT direct drive targets are the simplest around. LLE(U.Roch.) have made analogous capsules with the required specifications



LLE cryo target
X-ray phase contrast image
(courtesy D.Harding LLE)

Direct drive: A solution to the low ion kinetic energies in the foot pulse may be found in tamped "cannonballs"

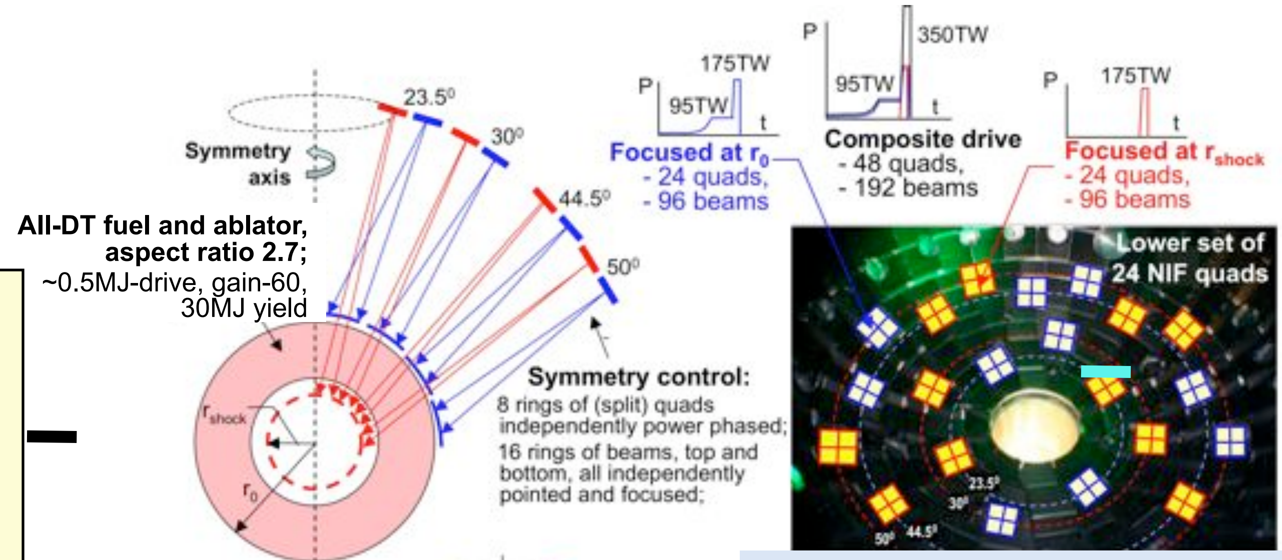
- **Tamped cannonballs (TCs) can be driven with a single high-energy (~2-10GeV) ion species**
- **TCs have high hydro efficiency ≤20% (combination of direct and radiation) that compensates for energy loss in tamp**
- **Addition of shock ignition may enable gains ~100 at ≥1MJ**
- **Further gain increases in gain are possible with zooming**



- Optimum ion species and kinetic energies TBD → Tradeoff between tamp thickness and drive efficiency
- Stability to be confirmed → Ion-driven instability (but low velocity, fat shells with high ablative ion-range/radiation smoothing)
- Two-sided polar drive geometry to be established → Will leverage NIF PPD optimization studies (but heavy-ions don't refract)

Direct drive: It is important to retain thick liquid wall options for heavy ion fusion $\Rightarrow$ Two- sided polar direct drive?

We are leveraging current NIF studies that are optimizing polar drive symmetry through pointing, focusing and power control

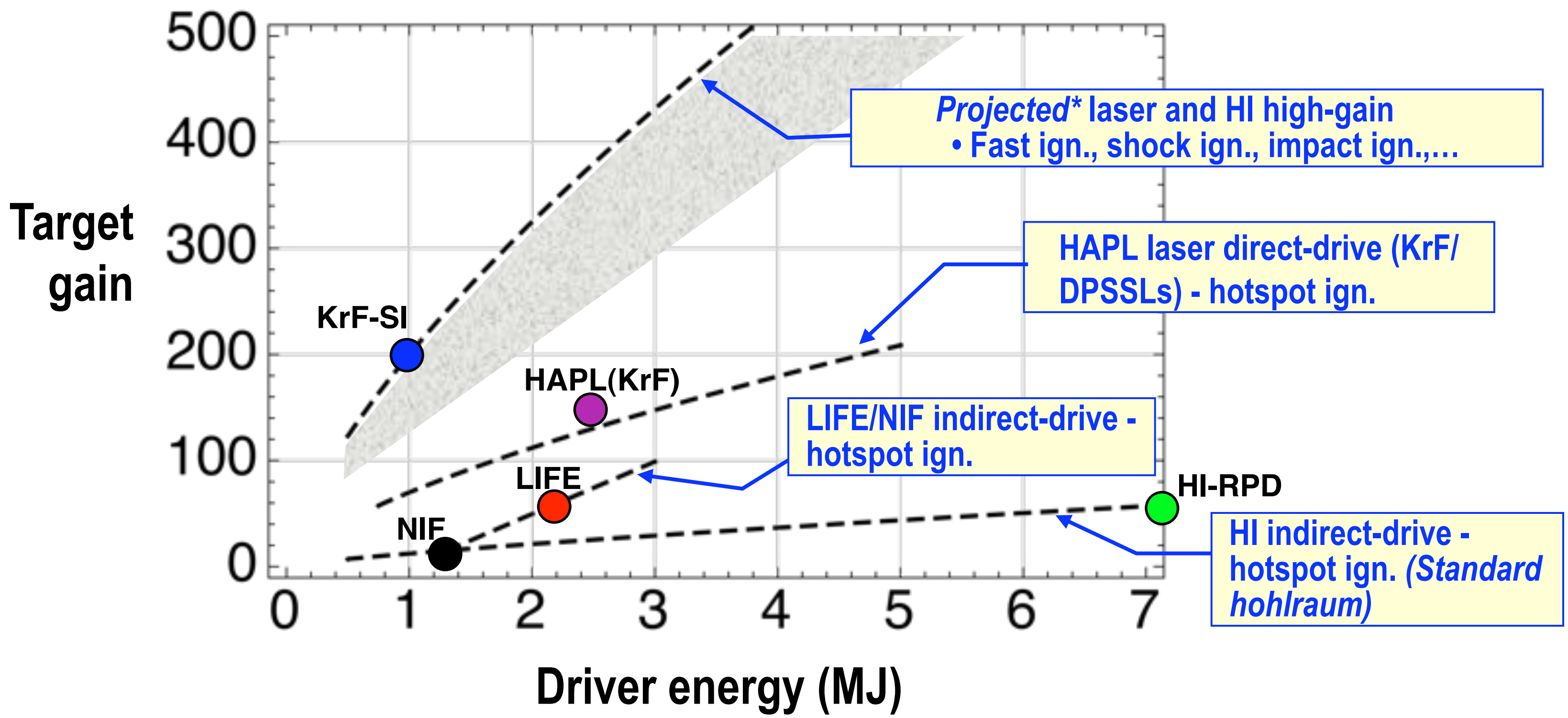


NIF lower 24 quads (96 beams)

Four annular rings of HI beams (15 each, 60 total) with hollow rotating spot can give ~0.7% intensity variations

J. Runge *Phys.Plasmas* 16 (2009)

Target for inertial fusion energy: Candidate gain curves...

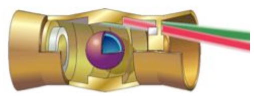


** Projected = projected in 1-D and initial 2-D studies but not fully established in integrated designs*

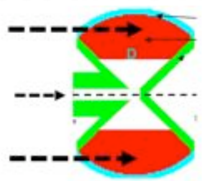
L.J.Perkins *Proc NAS Committee on Inertial Confinement Fusion Energy* Pleasanton CA Jan 2011

Where to from here: Modeling, simulation and experiments

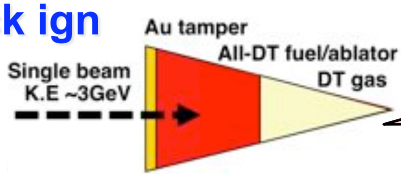
Indirect drive



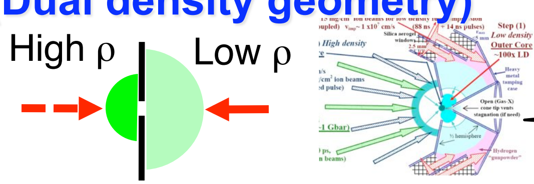
Direct drive X-target



Direct drive (tamped); shock ign



(Dual density geometry)



- Maintain point-of-departure design concepts
- Avenues for enhancement: Higher gain, single-side drive, single ion energy, shims...

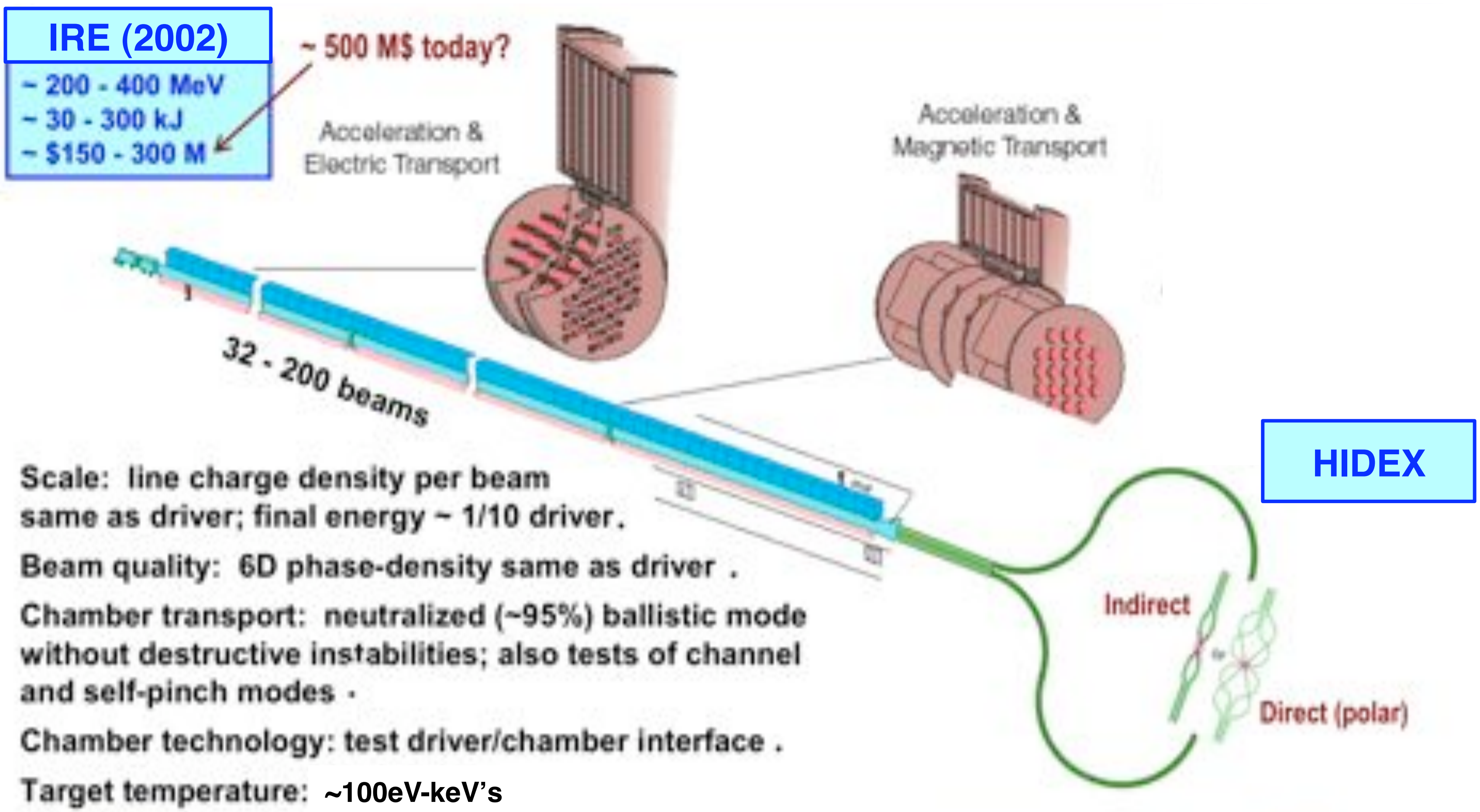
- Determine best ion species and k.energy
- Maximize assembled densities (≥100g/cm^3)
- Assess 2D-3D effects and mix
- Optimize (fast) ignitor energies and gain
- Integrate with practicable driver concept

- Determine best ion species and k.energy
- Optimize 1D energetics, ablator + shock ign.
- 2D PDD symmetry and zooming
- 2D-3D stability

- Maintain as a study project for high–yield targets and energy-conversion applications

....with input from NIF and Omega experimental data iterated with HIDIX accelerator target design using models improved with NDCX-II data.

The Heavy Ion Driven Implosion Experiment (HIDIX) would enable target implosion experiments at 10's-100's kJ



The Integrated Research Experiment (IRE) design from Snowmass-2002 could drive HIDIX for both direct and indirect drive targets

Heavy ion fusion development strategy: Target physics is integrated into the R&D phases to HIF-ETR/Demo

PHASE I: First 5 years: Integrated single beam accelerator experiments, benchmarked simulations, enabling technology development (e.g., magnet arrays), scaled liquid chamber experiments), **target designs for several target options, systems analysis.**

Decision

→ ***Deliverable:*** validation of selected heavy ion accelerator and target approach for Phase II & III

PHASE II: Next 10 years: Construct/operate 10-100kJ-scale Heavy-Ion-Driven Implosion Experiment (IRE-HIDIX), supporting liquid chamber, **target design,** target fabrication, injection R&D for **5 Hz burst-mode target experiments**. Technology development for Phase III.

Decision

→ ***Deliverable:*** validation of integrated multiple-beam accelerator, chamber & target design for Phase III

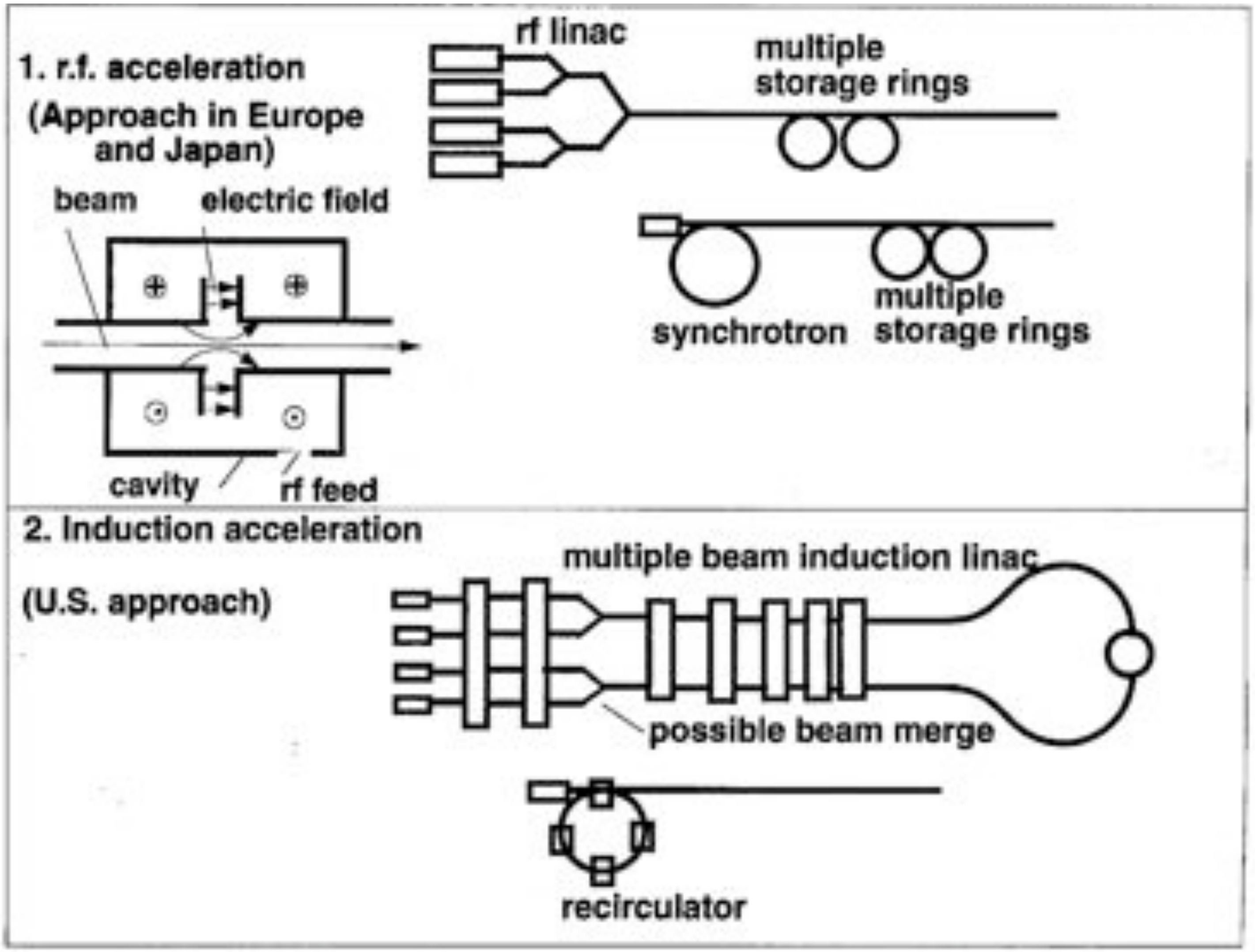
PHASE III: Next 20 years: Construct 2-3 MJ HIF ignition test facility for single shot tests, then burst mode, using accelerator designed for 5 Hz. If successful, add nuclear systems to upgrade to 150 MW average-fusion-power level HIF-ETR/DEMO.

B.G.Logan, *Proc NAS Committee on Inertial Confinement Fusion Energy* Pleasanton CA Jan 2011

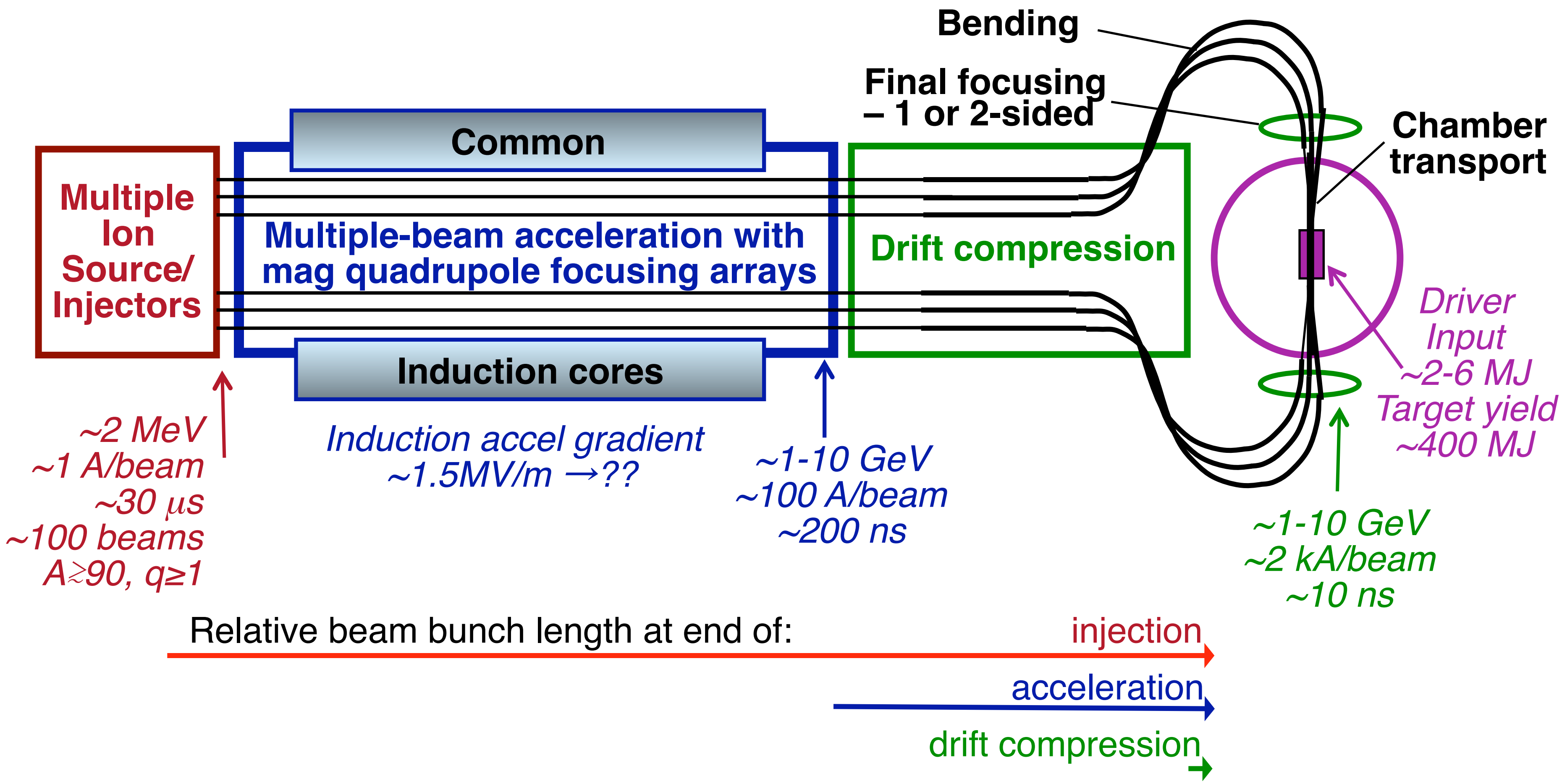
Backup slides

US IFE program: ~7 M$/yr (constant 2010 $) x 30 years~ $200 M(constant 2010 $)
~2 FTE/yr ave for 20years = ~10 M$ (constant 2010) - ~4% of NIF/NIC target effort

There are two principle methods of ion acceleration to GeV energies



We have established design baselines for multiple-beam quadrupole-focused induction linac drivers



Power amplification to required ~10TW per beam is achieved by acceleration and longitudinal bunching (drift compression) of mildly-relativistic ions

S.Yu *Fus Sci Techn.* 44 (2003)

Significant scale up of accelerator energy and peak power *@ relevant ion target range* is needed for an HIF driver.

	NDCX-II	GSI-SIS18	LHC	HIF driver
Ion energy	1.2→ 6 MeV (Li+)	70 GeV (U^{28+})	14 TeV (p)	10 GeV (Pb^{+})
Beam power	0.1 to 1 GW (50Ax2MeV →150Ax6MeV)	350 MW (in 130 ns)	1 TW (100 μs dump)	4 TW / beam X100 beams (in 8.2 ns)
Beam energy	0.08 to 0.25 J	45 J	100 MJ (total dump)	6 MJ
Space charge $\Delta\phi$/KE (final)	High 5×10^{-2}	Very Low 10^{-9}	Negligible	High to low 10^{-1} to 10^{-5}
Ion range	Low (~ 3 μm foil) 0.0001 g/cm^2	High (> WDM target) 10 g/cm^2	Way too high for IFE 10,000 g/cm^2	IFE target requirement 0.03 -1 g/cm^2

R&D roadmap to determine the feasibility of heavy ion fusion energy *(#'s=M$/yr)*

Fiscal Year	2009	2013	2014	2018	2019	2023	2024	2028	2029	2033
Integrated single beam HEDP/IFE exps. to maximize pressure in planar targets	7 M$/yr →	15	25 →	20	20 →	20	15 →	15		
NDCX-I (to 10 kBar)	7(@lbl	1 (@ PPPL)	→	5					Optimize plasma	
NDCX-II(1) (to 1 MBar)		12 →	13						Drift, bend & focus	
NDCX-II+→IB-HEDPX(1) (to 10 MBar)		1	10	13 →	11 →	6			Upgrade to 8 MV	
Intl. Collab. Exps. @ FAIR, LANSCE...		1	→	2 →	4	→ 9		→ 10	High KE ions	
(each row includes theory/sim and equipment support)			<5-yr Phase I >		Key decision (CD2 for HIDIX)					
Accelerator driver R&D for 5 Hz, multiple-beam target experiments	0.6 →	2.5	11 →	14	25 →	100	100 →	90		→90
5 Hz accelerator R&D (inc. HCX-II)(2)		1.5	8	8	15 →	15	15			
Exp. target R&D (design/fab/inj.)	0.3 →	0.5	1	2	2.5					
Long-path accelerator R&D(UMER,PT)	0.3 →	0.5	2 →	2	2.5					
Heavy Ion Driven Implosion Experiment (HIDIX) (5Hz, 100 MBar)				2 →	5	80 x 6 yr		80		
							Key Decision (CD2 for HIFTF)			
Heavy Ion Fusion Nuclear Science and Technology(3)	0.4	1.5 →	3	→ 5 →	20	→ 30 →	40	→ 75		→310?
5Hz HIF target design, fab, inj., tracking	0.3 →	1	2 →	2.5	10 →	15	20	→ 30		
Enabling liquid chamber R&D	0.1	0.5 → 1	→	2.5	10 →	15	20	→ 30		
Heavy Ion Fusion Test Facility (HIFTF) ~100 MJ yield single shot and 5 Hz								10 → 15		250 x 8 yr ? →
Fiscal Year	2009	2013	2014	2018	2019	2023	2024	2028	2029	2033
(All costs in M $ per year) Total HIF(1)	8 →	19	38 →	40	65 →	150	155	180		400?

(1) Budgets include HEDLP relevant to HIF, but not operations & diagnostic support for grant-funded HEDLP users

(2) Includes multiple beam injectors, transport, and final focus arrays needed for HIDIX

(3) Does not include MFE nuclear science and technology that may be applicable to HIF

Design | Construction | Operation/R&D

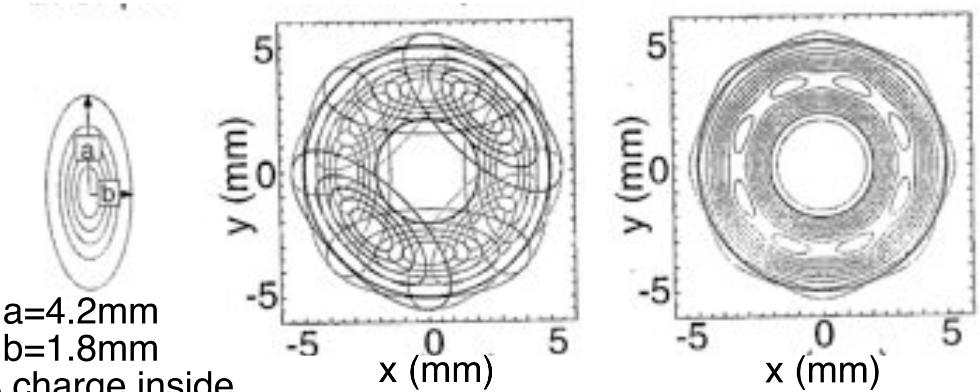
B.G.Logan, *Proc NAS Committee on Inertial Confinement Fusion Energy* Pleasanton CA Jan 2011

A deflecting *wobbler* field may be an effective technique for beam smoothing, uniform deposition and instability suppression

Conventional design uses multiple overlapping beams with static focii

Each beam is an ellipse

Eight beams overlap to give azimuthal symmetry (~1.5% m=8)



a=4.2mm
b=1.8mm
95% charge inside

Application of wobbler field is being investigated for producing annular hollow beams together with potential beam smoothing and R-T stabilization

H.Quin *Phys.Rev. Lett.* 104 (2010

Conjecture

"If a big accelerator lab had made a commitment to develop heavy ion fusion in 1975, as LLNL did for laser fusion, and had spent the same amount of money as was spent on either (a) laser fusion (~200M/yr x 30 years= ~6B$) or (b) high energy particle accelerators for science (~400 M x 30 yr=12 B$), it is virtually certain that a 5-10 MJ heavy ion accelerator would be available today for ignition studies.

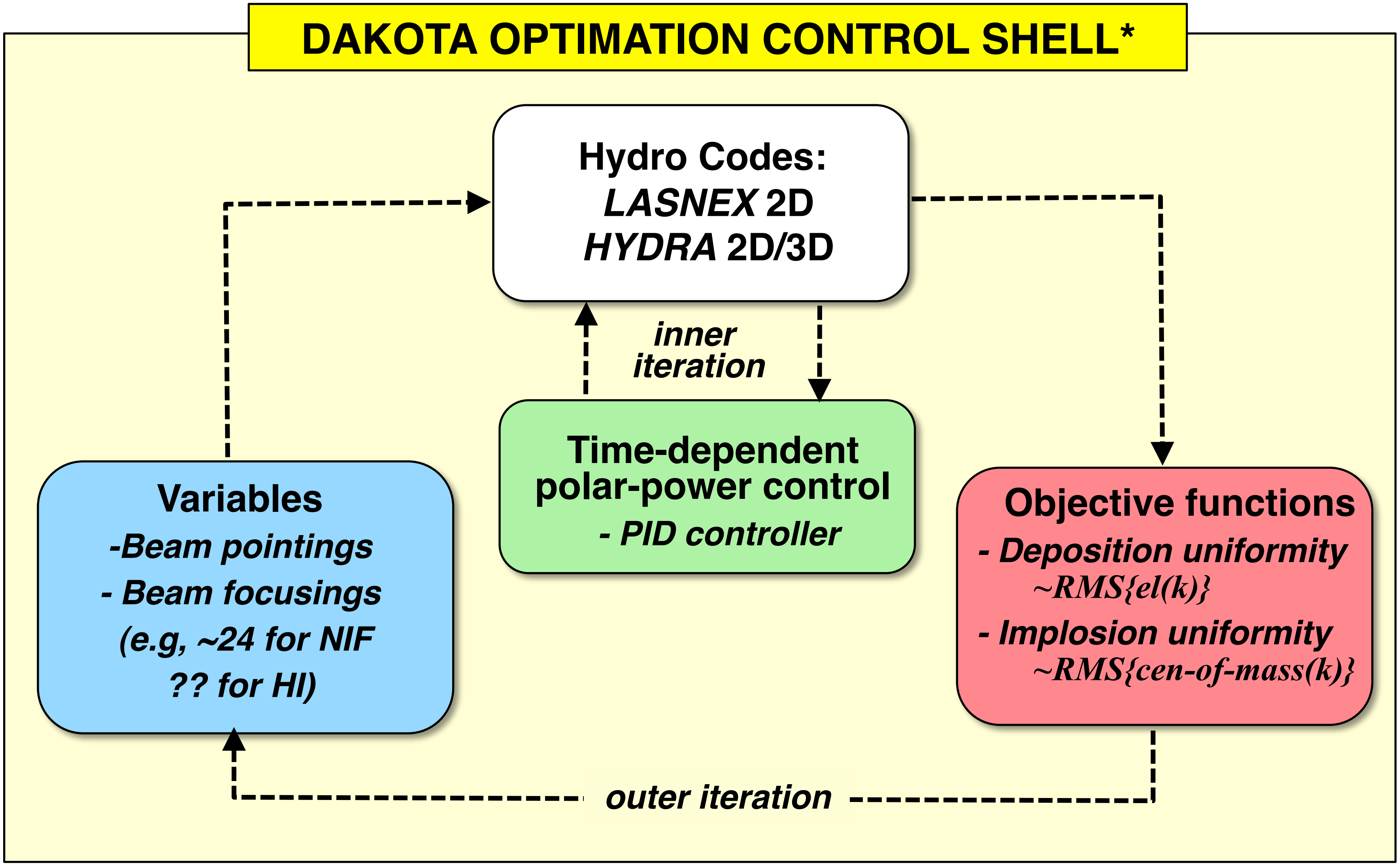
The accelerator would have evolved differently, towards ~3-10 GeV instead of ≥1TeV(to stop the beams in targets), and towards 50-100 parallel beams, instead of 1 beam (for illumination symmetry)."

B.G. Logan,

Director, Heavy Ion Fusion Science Virtual National Laboratory,

February 12, 2011.

Heavy Ion Polar Direct Drive: Our optimization formalism will exercise LLNL computation facilities to their limit

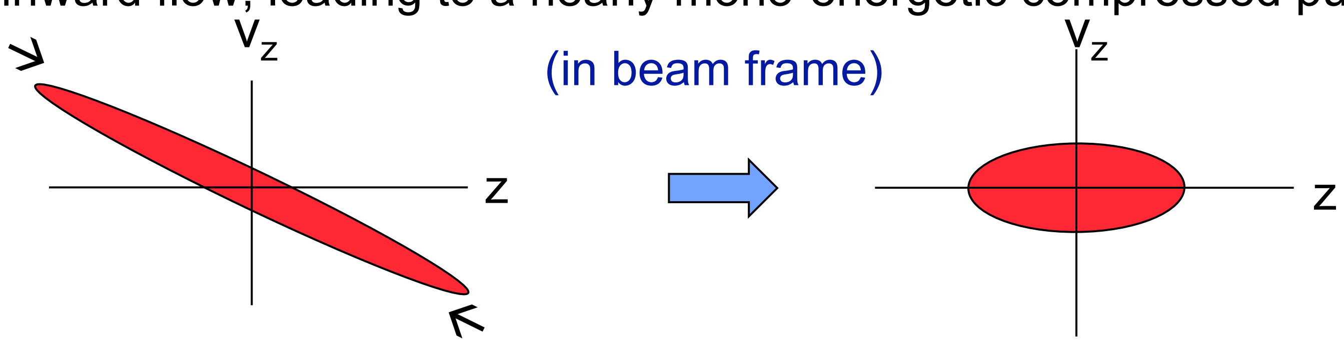


* DAKOTA – Sandia National Laboratory, http://www.cs.sandia.gov/DAKOTA/index.html (= "*UQ Pipeline*" at LLNL)

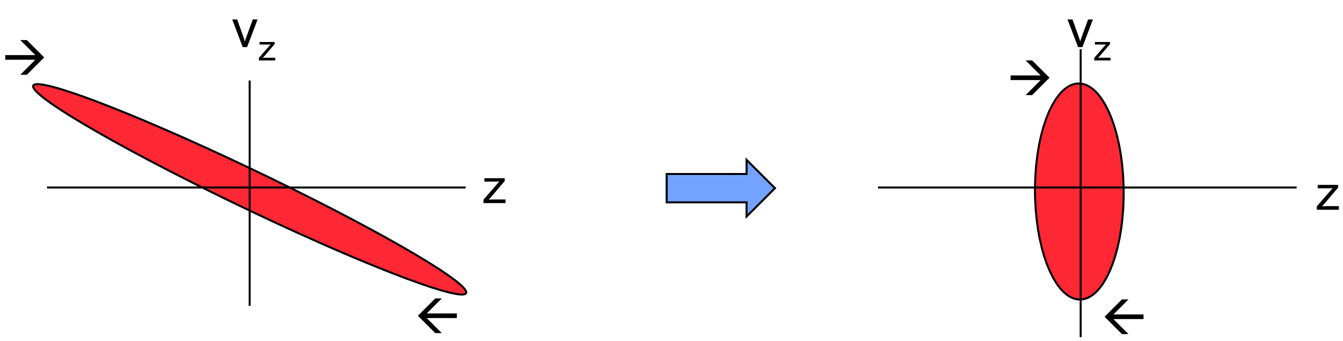
Drift compression is used to longitudinally compress an ion bunch

- **Induction cells impart a head-to-tail velocity gradient (“tilt”) to the beam**
- **The beam shortens as it “drifts” down the beam line**

- In **non-neutral drift compression**, the space charge force opposes (“stagnates”) the inward flow, leading to a nearly mono-energetic compressed pulse:



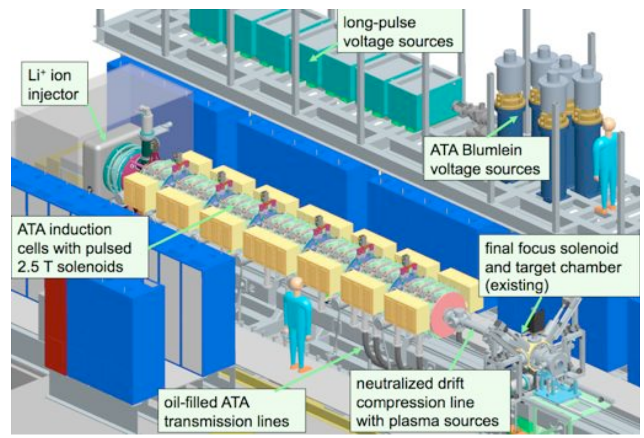
- In **neutralized drift compression**, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



Heavy Ion Fusion beam physics experimental/modeling status

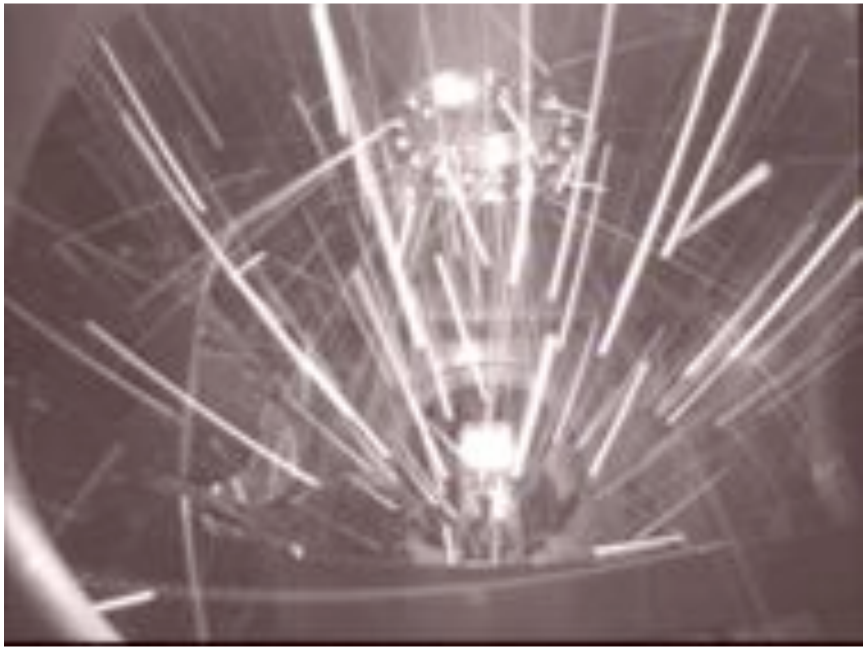
- Experiments and simulations have addressed most driver beam manipulations, giving confidence to projections of beam brightness on target.
  - Most had currents of 10–20 mA but driver-like dimensionless parameters, *e.g.,* perveance ($\propto$ current/velocity^3) and "tune depression" (space charge defocusing)

  - The Neutralized Drift Compression Experiment-II (NDCX-II) at LBNL should reach ~100A on target →

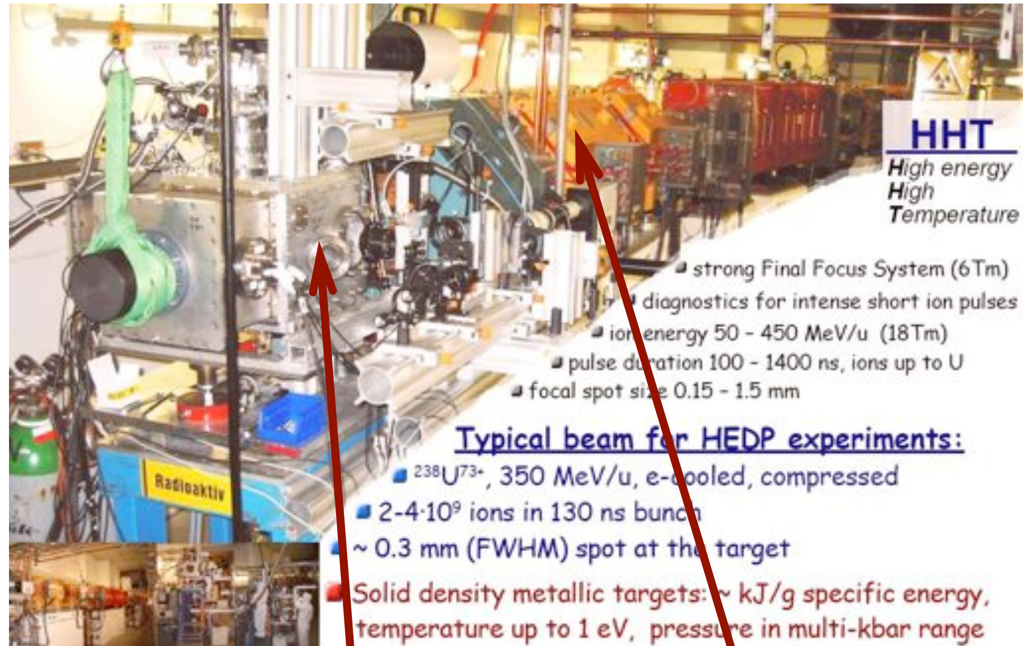


- Studies of heavy ion power plants predict a COE similar to that of other fusion options, assuming that:
  - it'll be possible to fabricate targets inexpensively
  - liquid-wall target chambers can be cleared rapidly
  - cost-effective drivers can be built.

VNL targets have been heated with 0.3 A, 83 GeV U^{+73} ions focused to 150μm radius spots on target at GSI Darmstadt



Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 130 ns, 50 J heavy ion beam to ~ 1 TW/cm^2 peak and 1 eV in joint experiments at GSI, Germany.



Diagnostic optics | **Final focus magnets**

The new FAIR upgrade of GSI's accelerator will allow joint cryo hydrogen compression experiments relevant to heavy ion fusion with much more (80 kJ) of uranium beam energy.

Ion stopping in HYDRA and LASNEX rad-hydro target codes

$$-\frac{dE}{dx} = \underbrace{\left[\frac{4\pi e^4}{m_e c^2}\right]}_{5.1e-22\ keV\ cm^2} \underbrace{\left[\frac{N_0 \rho_T}{A_T}\right]}_{} \left[\frac{Z_{eff}^2}{\beta^2}\right] \left\{ (Z_T - \overline{Z}) \operatorname{Log} \Lambda_B + \overline{Z}\, G(\beta / \beta_e) \operatorname{Log} \Lambda_F \right\}$$

ρ_T = target density in g/cm^3, A_T = target atomic weight

Z_T = target atomic number, $\overline{Z}$ = target ionization state

$$\Lambda_B = \frac{2 m_e c^2 \beta^2}{\bar{I}}, \quad \Lambda_F = \frac{m_e c^2 \beta^2}{\hbar \omega_p}, \quad G(x) = erf(x) - x\, erf'(x) = 1 \text{ for } x >> 1$$

$\bar{I}$ = average ionization potential $= .01 Z_T\ keV$ (Bloch's rule)

ω_p = plasma frequency $= \sqrt{4\pi e^2 n_e / m_e} = 56416 \sqrt{n_e}$ /sec

$\hbar \omega_p = (3.7e-14)\sqrt{n_e}\ keV$, n_e = electron density in $1/cm^3 = \overline{Z} N_0 \rho_T / A_T$

Ion Beam : $\beta = v/c$, $\gamma = \dfrac{1}{\sqrt{1-\beta^2}} = 1 + \dfrac{E}{Mc^2}$

E = Kinetic Energy of Ion Beam in keV,

Mc^2 = Ion Beam Rest Energy $= A_{ionBeam}\ (9.3e5)\ keV$

$m_e c^2$ = Electron Rest Energy $= 511\ keV$

Betz Empirical $Z_{eff} = Z_{ionBeam}\left[1 - \exp(-137\, \beta_{eff} / Z_{ionBeam}^{.69})\right]$

$\beta_{eff}^2 = \beta^2 + \beta_e^2$, with $\gamma_e = \dfrac{1}{\sqrt{1-\beta_e^2}} = 1 + \dfrac{kT_e}{m_e c^2}$

Relativistic Correction : $\operatorname{Log} \Lambda_B \to \operatorname{Log} \Lambda_B + R$, $\operatorname{Log} \Lambda_F \to \operatorname{Log} \Lambda_F + R/2$

where $R = 2 \operatorname{Log} \gamma - \beta^2$